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# THE DEVELOPMENT AND VALIDATION OF AN AUTOMATED HEADBOARD DEVICE FOR MEASUREMENT OF THREE-DIMENSIONAL COORDINATES OF THE HEAD AND FACE

BY

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This report describes the development of an automated headboard device (AHD) for measuring three-dimensional coordinates of landmark locations on the head and face. Designed to be operated in conjunction with a portable computer which contains special software, the AHD produces on-line measurements which are compatible with the existing headboard data base (heights and depths), yet expands the information to include breadths. The device was developed for use in the 1987-1988 anthropometric survey of Army personnel. In its first field application, the AHD was programmed to measure 26 head and face landmarks selected on the basis of their usefulness in the design and construction of helmets, respirators, goggles, and other personal protective equipment.

A series of validation tests demonstrated that: (1) the AHD provides 3-D coordinates at nearly twice the speed as similar data obtained by traditional methods, (2) both intra- and interobserver error obtained with the AHD are less than those obtained with the

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19. (continued) ABSTRACT

traditional technique, and (3) the ability of operators to duplicate coordinate values of other operators nearly as well as they were able to duplicate their own, appeared to confirm the reliability of the device in the hands of different operators.

Included in this liberally illustrated report are detailed descriptions of how the AHD is designed and how it functions. A number of appendices provide drawings of component layouts, parts lists, software, and a user's manual.

## PREFACE

This report describes the development and validation testing of an automated headboard device (AHD) which was completed in fulfillment of Task IV under contract DAAK60-86-C-0128 with the U.S. Army Natick Research, Development and Engineering Center, Natick, Massachusetts. The contract monitor was Dr. Claire C. Gordon of the Science and Advanced Technology Directorate.

Using concepts developed by the U.S. Army and Anthropology Research Project, Inc., the AHD was engineered and constructed under contractual arrangements with Mr. Jerome E. Deis of PJ Measurement Systems, Dayton, Ohio. With expertise in coordinate measurement technology, Mr. Deis directed the construction of the AHD by Design Technologies and Manufacturing of Troy, Ohio. The authors would also like to acknowledge the contributions of Mr. Jeff Meredith of Design Technologies and Manufacturing and Mr. Paul Hawthorne of PJ Measurement Systems. Without the special diligence and cooperative attitude manifested by these individuals, an instrument with the complexity of the AHD could not have been completed within the allotted time period.

For their support and creative input thanks are due to Dr. John McConville, Dr. Bruce Bradtmiller and Mr. Charles Clauser of Anthropology Research Project. Gratitude goes also to Mr. Thomas Churchill and Ms. Jo Ross for their efforts in developing the rotation and editing programs. Special thanks to Dr. Robert Beecher of Beecher Research Company, who provided the framework of the rotation program for this application.

The authors gratefully acknowledge the contributions of Ms. Ilse Tebbetts for the many hours of editing, of Ms. Jane Reese for her organizational skills in managing the production of this report, and of Ms. Belva Hodge and Ms. Lori Deen for many hours of word-processing. All the illustrative drawings in this report were executed by Mr. Gary Ball. Last, but not least, the authors thank all of those Anthropology Research Project, Inc. staff members who served as test subjects during the validation testing of the AHD.

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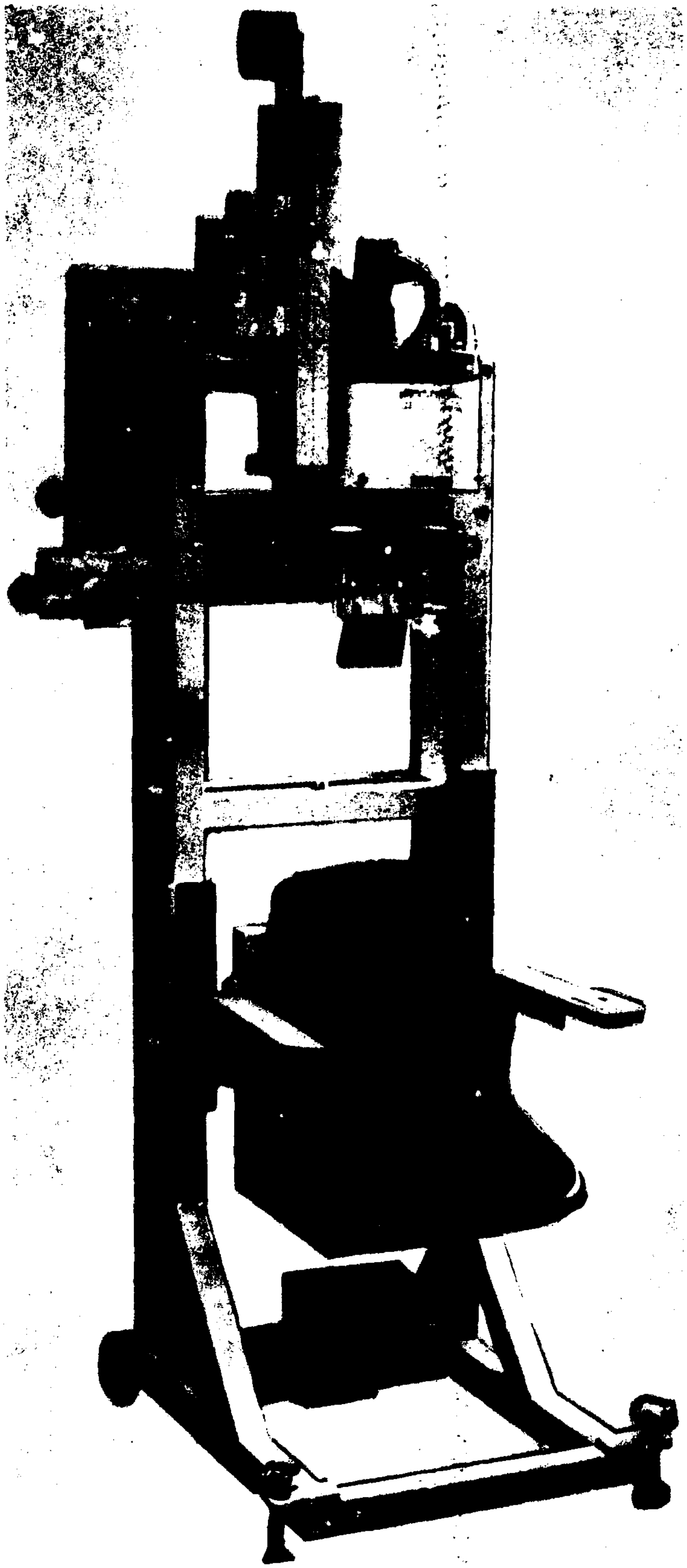


The Automated Headboard Device

# THE DEVELOPMENT AND VALIDATION OF AN AUTOMATED HEADBOARD DEVICE FOR MEASUREMENT OF THREE-DIMENSIONAL COORDINATES OF THE HEAD AND FACE

## INTRODUCTION

The measurement of three-dimensional (3-D) coordinates of the surface of the human body finds its justification in the applicability of such anthropometric information to the design of personal protective items for the head and face where good fit is critical. In the future, anthropologists and engineers will utilize remote imaging devices, such as lasers, video cameras, and holographic systems, to collect great quantities of 3-D shape information very rapidly. The measurement accuracy of such devices as well as the statistical means for analyzing large-sample data are still under investigation, however. For the present, we must be satisfied with 3-D information on a relatively low number of body landmark locations, particularly when measured on large samples under field survey conditions. The area of the body for which the collection of 3-D information in a major anthropometric survey seems most warranted is the head and face. The head and face are perhaps the most difficult body parts to be adequately described by traditional linear or curvilinear measurement techniques because of the great variability of head and facial dimensions and their associated poor correlations. Yet the fit requirements for respirators, eyeglasses, and other head/face gear are extremely high.

ANTHROPOMETRY, PROTECTIVE EQUIPMENT, HEAD, EYES. (JES)

It was the objective of this project to develop a device which could provide accurate and reliable measurements that would be compatible with the existing headboard data base yet be truly three-dimensional and permit on-line computer processing of the data. An additional goal was to reduce the per-point measurement time compared to traditional techniques.

## BACKGROUND

The need for a more detailed metric description of the head and face was recognized quite early in the history of modern anthropometric surveys. Major U.S. surveys, those in which large numbers of measurements have been made on samples of a thousand or more individuals, have been carried out exclusively on military personnel. The rudiments of coordinate definition of a number of head and face landmarks were initiated in the 1950 U.S. Air Force survey of flying personnel.[1] In this survey of 4,000 males, the rectilinear distance between each of four landmark locations and a plane surface (wall) was determined. The landmarks were ectocanthus, nasal root depression (sellion), tragion, and the larynx. In addition, tragion was measured to the top of the head (vertex). Since bitragion breadth was also measured, one could assign coordinate values within the Cartesian axis system to the right and left tragion landmarks, if one assumes that the vertex is centered in the system.

The Cartesian axis system as typically applied to head and face measurements is depicted in Figure 1. The zero reference for the axes X, Y, and Z ($X_0$, $Y_0$, $Z_0$) lies at the intersect of two plane surfaces in contact with the top (vertex) and the back of the head and at a point in the midsagittal plane. Measurements originating from the rear plane and projecting perpendicularly forward are said to be in the +X direction, whereas measurements projecting perpendicularly downward from the top plane are in the +Z direction. Measurements to the right and left of the subject's midsagittal plane would be in the -Y and +Y direction, respectively, although measurements on the Y axis have not customarily been made due to lack of an easily definable reference. With the subject's head in contact with the two reference plane surfaces, the +X and +Z distance to any given landmark may be measured. Such measurements have come to be known as headboard measurements. By 1960 the utility of such measurements had apparently been recognized, since a special headboard device was designed and constructed for use in an anthropometric survey of the military forces of three NATO countries -- Turkey, Greece, and Italy. The survey was organized and directed by Dr. H.T.E. Hertzberg, a USAF anthropologist.[2] The design of the device, which has come to be known as the NATO headboard, is described in the referenced publication. It consisted of two plywood plane surfaces which were fixed at right angles. The posterior of the head contacted the vertically mounted rear plane and the top of the head contacted the adjustable horizontal plane surface. Once the horizontal piece was positioned to comfortably accommodate the subject's standing height and locked in place, the subject's head was oriented in a standard position called the Frankfort plane. The head in this case is said to be in the Frankfort plane when the right tragion and right infraorbitale landmarks are aligned in a plane perpendicular to the rear headboard and parallel to the top headboard (see Figure 2). Six landmarks were measured in the NATO survey. Using a height/depth gauge, the distance to each landmark was measured from the rear plane (from the wall) and from the top plane (from the vertex).

Following the NATO survey, the same basic headboard has been used in a total of five U.S. military surveys. A listing of all of the surveys in which headboard or headboard-like data have been collected is presented in Table 1 (measured dimensions indicated by Xs).[1,2,3,4,5,6,7,8,9,10,11] So far as is known, no such measurements have ever been collected on U.S. civilians.

The principal known use of the headboard data has been to provide orthogonally organized dimensions for the construction of 3-D forms used as design guides in respirator sizing systems.[12] Headboard data have also been useful in specifying other head or facial appliances; however, despite the undisputed value of the information, little was apparently done through the years to improve the measurement techniques or to develop instrumentation which would provide true 3-D coordinate data without recourse to caliper-measured breadths from bilateral landmarks. The NATO headboard is not only awkward for both subject and measurer, but also prone to inaccuracies due to subject movement and variations in subject and gauge positioning. In order to address some of these measurement problems, a somewhat mechanized version of a headboard was developed in Britain for use in the 1970/1971 anthropometric survey of

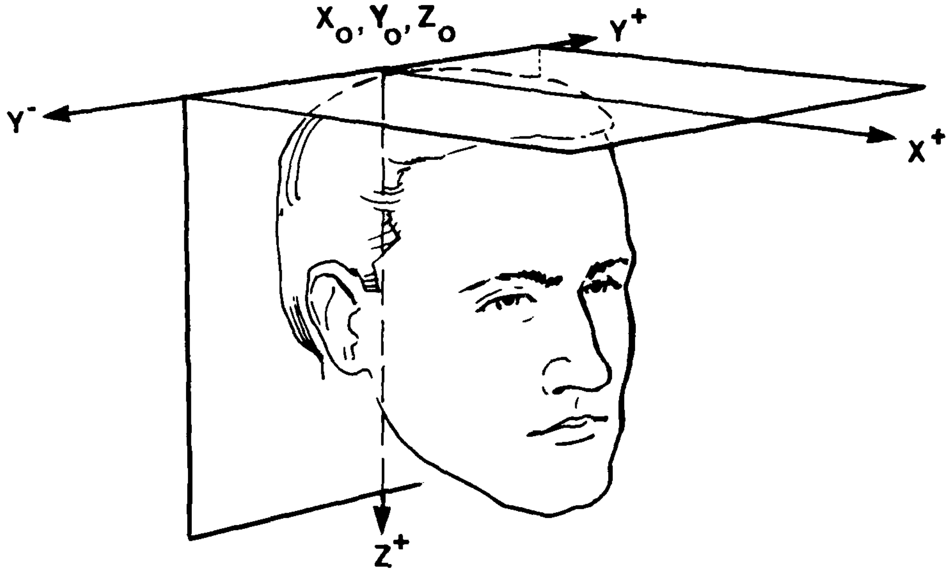



Figure 1. Axis system for headboard measurements.

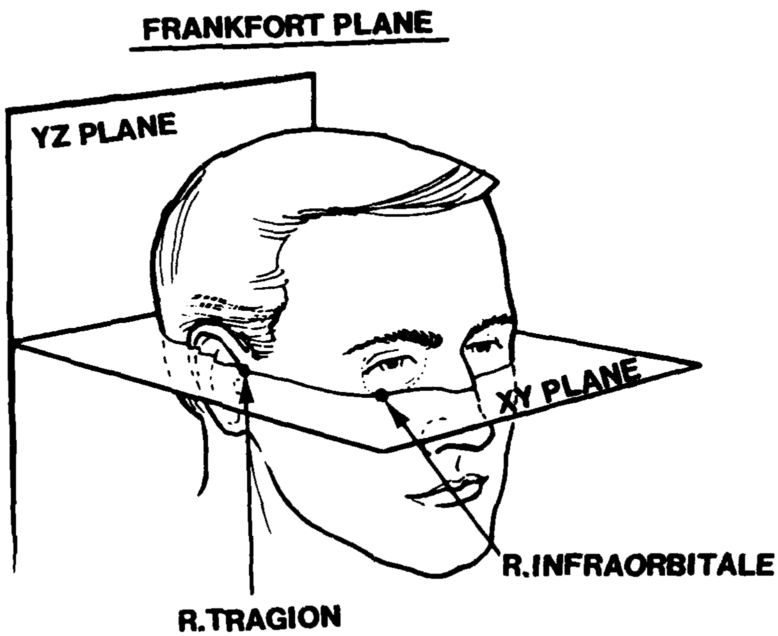



Figure 2. Diagram showing the key landmarks and the reference planes typically used in defining the Frankfort plane for headboard measurements.

TABLE 1. Summary of Available Headboard Data -- U.S. Military and NATO Surveys.

| Measurement | 1950* USAF Flyers (n=4000) | 1960-61 NATO Soldiers (n=3099) | 1965 USAF Personnel (n=3869) | 1966* US Army (n=6682) | 1967 USAF Flyers (n=2420) | 1970 US Army Aviators (n=1482) | 1964* US Navy Flyers (n=1529) |
|---|---|---|---|---|---|---|---|
| Chin Prominence-Wall | -- | -- | -- | -- | X | -- | -- |
| Ectocanthus-Vertex | -- | X | X | -- | X | -- | -- |
| Ectocanthus-Wall | X | X | X | X | X | X | X |
| Glabella-Vertex | -- | X | X | -- | X | X | -- |
| Glabella-Wall | -- | X | X | -- | X | -- | -- |
| Larynx-Wall | X | -- | -- | -- | -- | -- | -- |
| Lip Prominence-Wall | -- | X | X | -- | X | -- | -- |
| Menton-Vertex | -- | X | X | -- | X | -- | X |
| Menton-Wall | -- | X | X | -- | -- | -- | -- |
| Nasal Root Depr-Vertex | X | X | X | -- | X | -- | -- |
| Nasal Root Depr-Wall | X | X | X | X | X | X | X |
| Pronasale-Vertex | -- | X | X | -- | X | -- | -- |
| Pronasale-Wall | -- | X | X | X | X | X | X |
| Stomion-Vertex | -- | X | X | -- | X | -- | -- |
| Stomion-Wall | -- | -- | -- | -- | -- | -- | -- |
| Subnasale-Vertex | -- | -- | -- | -- | X | -- | -- |
| Subnasale-Wall | -- | -- | -- | -- | X | -- | -- |
| Tragion-Vertex | X | X | X | X | X | X | X |
| Tragion-Wall | X | X | X | X | X | X | X |

* NATO type headboard not used; listed measurements were performed with an anthropometer or beam caliper

TABLE 1. Continued

| Measurement | 1966* US Navy Enlisted (n=4095) | 1966* Marines Enlisted (n=2008) | 1981* US Navy Aircrew (n=1087) | 1968 USAF Women (n=1905) | 1977 US Army Women (n=216) | 1982* US Navy Women (n=352) |
|---|---|---|---|---|---|---|
| Chin Prominence-Wall | -- | -- | -- | -- | -- | -- |
| Ectocanthus-Vertex | -- | -- | -- | X | X | -- |
| Ectocanthus-Wall | X | X | X | X | X | X |
| Glabella-Vertex | -- | -- | -- | -- | X | -- |
| Glabella-Wall | -- | -- | -- | -- | X | -- |
| Larynx-Wall | -- | -- | -- | -- | -- | -- |
| Lip Prominence-Wall | -- | -- | -- | X | -- | -- |
| Menton-Vertex | -- | -- | -- | X | X | -- |
| Menton-Wall | -- | -- | -- | X | X | -- |
| Nasal Root Depr.-Vertex | -- | -- | -- | -- | X | -- |
| Nasal Root Depr.-Wall | X | X | X | -- | X | X |
| Pronasale-Vertex | -- | -- | -- | X | X | -- |
| Pronasale-Wall | X | X | X | X | X | X |
| Stomion-Vertex | -- | -- | -- | X | X | -- |
| Stomion-Wall | -- | -- | -- | -- | X | -- |
| Subnasale-Vertex | -- | -- | -- | X | X | -- |
| Subnasale-Wall | -- | -- | -- | X | X | -- |
| Tragion-Vertex | X | X | X | X | X | X |
| Tragion-Wall | X | X | X | X | X | X |

* NATO type headboard not used; listed measurements were performed with an anthropometer or beam caliper.

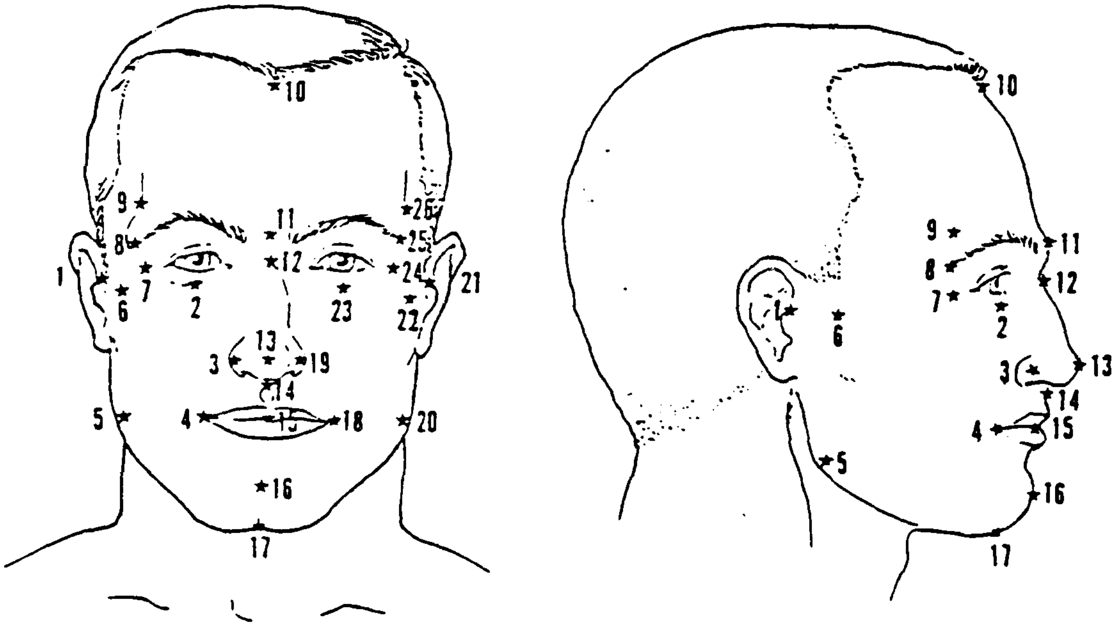
2,000 Royal Air Force (RAF) aircrew.[13] Using mechanical joints and scales fixed to the vertical and horizontal reference planes, a pointer positioned on a given landmark could provide simultaneous distance values from both surfaces. Mirrors were used to assist in the alignment process and to reduce random movement. This device has since been adopted by the U.S. Air Force in the Integration Laboratory at Brooks AFB, Texas. The RAF headboard, although an improvement over the original NATO headboard, does not provide landmark locations in 3-D and could not be easily instrumented for computerized data collection.

The development of an automated headboard device (AHD) was undertaken under U.S. Army contract DAAK60-86-C-0128 in preparation for the 1987-1988 Anthropometric Survey of U.S. Army soldiers. Since the development time was short, advantage was taken of existing technology where possible, but the AHD described in this report incorporates a number of new approaches to solving measurement and subject handling problems. The report details the design, function, and operation of the AHD as organized by the major subsystems involved. A summary analysis of the validation testing results is also included. A number of appendices provide detailed drawings of component layouts, parts lists, software, and a user's manual.

## THE 1987-1988 U.S. ARMY ANTHROPOMETRIC SURVEY

Twenty-six head and face landmarks were selected for measurement in the U.S. Army anthropometric survey (ANSUR) for which the AHD was first developed. These are listed and illustrated in Figure 3 and described in Appendix A. In order to establish the relative magnitude of subject movement during a given measurement period, two landmark measurements, R Tragion and Sellion, were repeated at the end of each session. These data also make possible editing options (see p. 27).

The measurements were chosen on the basis of their usefulness in the design and construction of helmets, respirators, goggles, and other personal protective equipment. The order of the measurements was selected to minimize the time required to complete the collection of a full data set. Early trials of the AHD and all final validation studies of the device, were made on this set of landmarks. It should be noted that the AHD can be used to obtain 3D coordinates on any number of other points on the head, face, or other body part of similar volume with adaptation of the software to a new list of landmarks.




1. R Tragion
2. R Infraorbitale
3. R Alare
4. R Cheilion
5. R Gonion
6. R Zygion
7. R Ectoorbitale
8. R Zygofrontale
9. R Frontotemporale
10. Crinion
11. Glabella
12. Sellion
13. Pronasale
14. Subnasale
15. Stomion
16. Promenton
17. Menton
18. L Cheilion
19. L Alare
20. L Gonion
21. L Tragion
22. L Zygion
23. L Infraorbitale
24. L Ectoorbitale
25. L Zygofrontale
26. L Frontotemporale

Sellion (repeat)
R Tragion (repeat)

Figure 3. <u>Landmark locations in order of measurement (U.S. Army survey, 1987-1988).</u>

## DESCRIPTION OF THE AHD

The AHD was designed and constructed* for the accurate measurement of 3-D coordinates of selected landmarks of the head and face in accordance with the axis system shown in Figure 1. The postural configuration of the head during measurement produces data which are reasonably compatible with the existing headboard data base, yet the information obtained is truly three-dimensional for the first time. The AHD is said to be automated because the operator need only lightly touch a drawn landmark with the tip of a probe in order to record the coordinates. Although designed to be operated in conjunction with a portable personal computer which has been programmed for use in head/face measurements, the device could be used equally well to determine point coordinates on the surface of any object that may be contained within its operational volume.

A drawing of the complete AHD is shown in Figure 4. Overall the device is 215 cm (85 in) high, 64 cm (25 in) wide, 122 cm (48 in) deep; it weighs approximately 90 kg (198 lbs). The AHD consists of a tubular steel frame (2-inch square) which supports the subject positioning system (SPS), the instrumentation and hardware comprising the coordinate measuring system (CMS), and the various subassembly controls necessary for safe and repeatable operation. The support frame also serves as a transport "dolly" to facilitate movement from site to site in field operations. Subjects are seated during the measurement procedure. The molded plastic seat pan is equipped with an electrically powered lift system, which may be controlled by the subject. A motor driven linear actuator raises and lowers the seat, and permits the accommodation of persons with sitting heights of 74 cm (29 in) through approximately 104 cm (41 in). The chair lift raises the subject into the head positioning subassembly located just under the rotary support housing near the top of the support frame (see Figure 4). Some of the details of this equipment are illustrated in Figure 5.

---

* The AHD was designed and constructed to specifications developed at Anthropology Research Project by PJ Measurement Systems, Dayton, Ohio, in collaboration with Design Technologies and Manufacturing Company, Troy, Ohio. Included with the AHD as delivered was the basic software required for calibration and for the measurement of 3-D coordinates for the head and face landmarks listed in Figure 3.

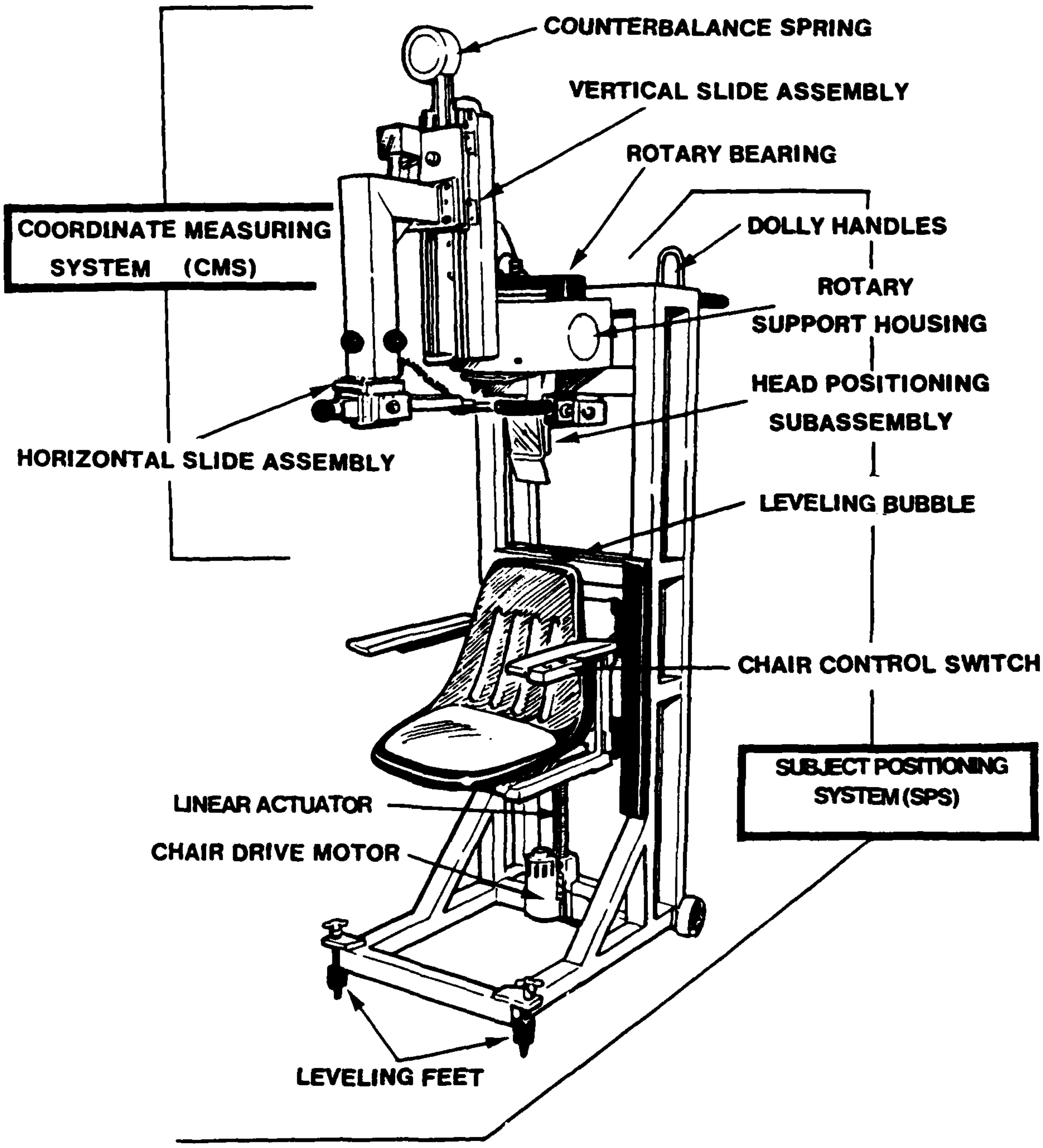



Figure 4. Principal components of the automated headboard device (AHD).

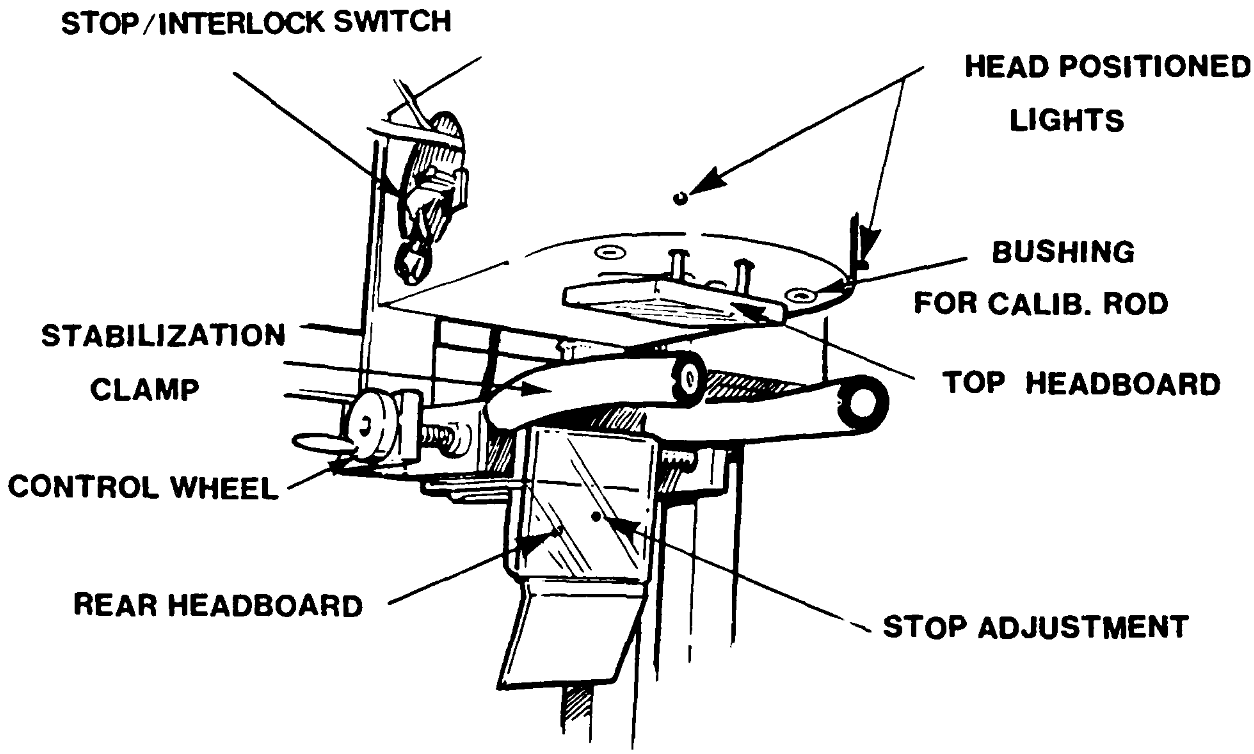



Figure 5. The head positioning subassembly.

The top headboard and rear headboard from which the Z axis and the X axis, respectively, take their origins, are constructed of clear plastic. When the seated subject's head is "tight" against both headboard surfaces, the headboards are forced into a right angle position, activating the lights located on the front-lateral aspects of the housing to indicate that the head is positioned correctly. Flanking the headboards is the stabilization clamp designed to center the subject's head in the system and to minimize whole-head rotational movements during the measurement process.

The instrumentation and hardware that comprise the CMS, exclusive of the computer and the related software, are also suspended from the top of the support frame. Mechanically, the CMS consists of a moveable arm, which has three degrees of freedom of movement: in and out (horizontal axis slide mechanism), up and down (vertical axis slide mechanism), and around the subject's prepositioned head (rotary axis bearing). These movements, their approximate range, and their related assemblies are depicted in Figure 6.

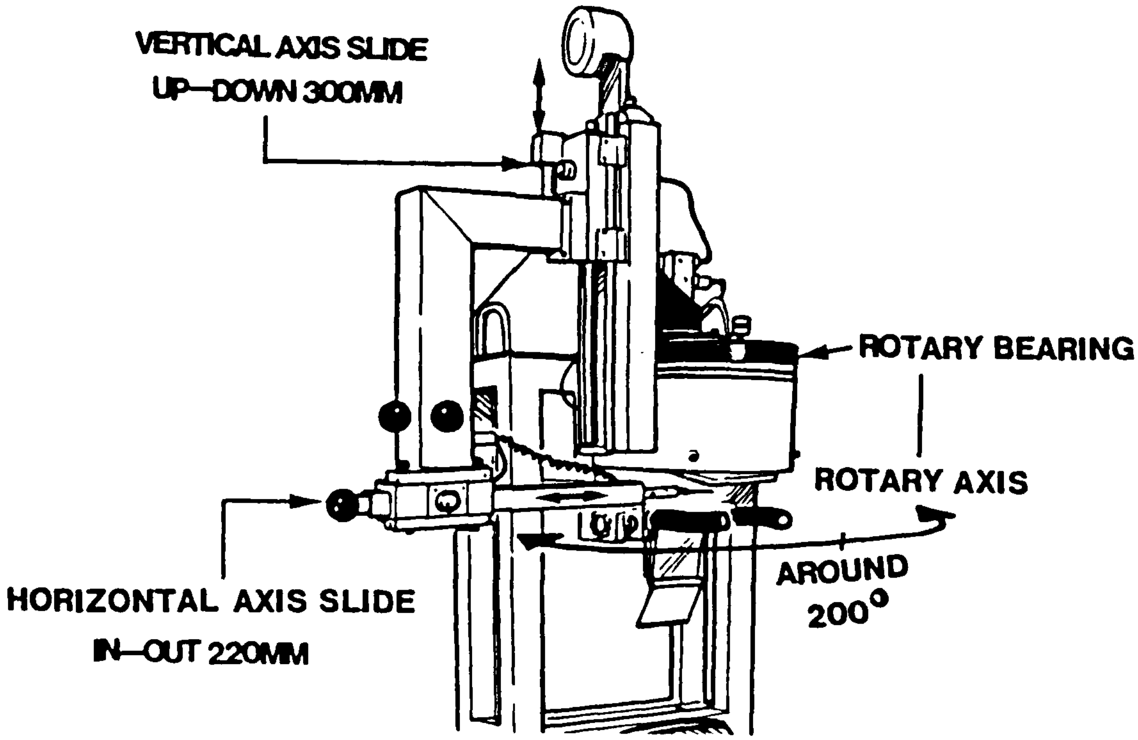


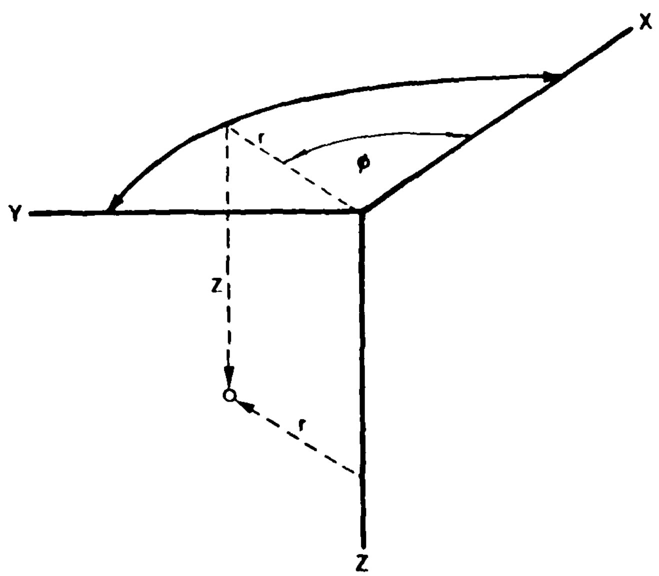

Figure 6. *The axis assemblies of the coordinate measuring system (CMS).*

The purpose of the movement is to permit the operator to place a small ruby bead (2 mm diameter) located on the tip of the touch probe of the horizontal slide in contact with each of the drawn landmarks to be measured. When in position the coordinates for a given landmark may be recorded automatically by applying light pressure on the bead (auto trip mode) or manually without pressure via a remote hand-held switch (manual trip mode). Simply put, the CMS must "know" at all times the exact X-Y-Z location of the center of the bead. How the CMS does this and how well it does it is the subject of following sections of this report.

## THE COORDINATE MEASURING SYSTEM (CMS)

Three-dimensional coordinate determination requires the ability to measure distance along three orthogonal axes in relation to some defined reference location. The reference location or origin is the same for each axis and may be located within or outside of the object being measured. Traditionally, the principal axes are labelled X,Y, and Z. Specifications require that the CMS must be able to resolve $\leq$ 0.10 mm along each axis. In order to accomplish this, each moveable element, i.e., vertical, horizontal, and rotary, is equipped with a sensitive "distance" transducer, which provides distance information to the accompanying computer from which the coordinates

are calculated on-line. The measuring device in each element is an encoder that converts movement into electrical pulses, which are equivalent to linear distance or angular change (e.g., radians). Encoders of this type are frequently used in precision coordinate measuring machines in industry, and to provide positional feedback to robotic control systems. The encoders incorporate a central shaft, which is caused to rotate with movement by means of a rack and pinion mechanism. These devices are frequently called rotary, shaft, or optical encoders. The shaft is attached to a finely etched grating which when rotated alternately interrupts or transmits a light beam focused on photocells. Each interruption, equivalent to one grating pitch, establishes the output signal of the encoder. The density of the etched lines determines the sensitivity of an encoder. The vertical and horizontal axis encoders of the CMS each have 50 lines/millimeter of scan surface which, when translated into distance, provide a resolution of 0.02 mm. The rotary axis encoder has a sensitivity of less than 0.01 mm. Each encoder is equipped with its own signal conditioner which converts the pulses into square waves. The conditioned signals are conducted to the computer via a shielded cable where the software counts each pulse, totals the counts for the movements in each axis, and performs the necessary calculations to provide X, Y, and Z coordinate values. The rotary axis encoder supplies angular change (of the CMS arm) information which, when combined with the input of the horizontal axis encoder, enables the computation of the coordinates for X and Y. The vertical axis encoder measures the Z distance directly without need for trigonometric calculations. When all three inputs are combined, the computations are essentially those of a cylindrical coordinate system. In other words, a polar coordinate system extended to three dimensions becomes a cylindrical coordinate system. The trigonometric relationships which apply are given in Figure 7.




$$X = r \cos \phi$$
$$Z = Z$$
$$r = \sqrt{X^2 + Y^2}$$
$$\phi = \tan^{-1} \frac{Y}{X}$$
$$Y = r \sin \phi$$

Figure 7. Trigonometric relationships used in the computation of coordinates in the CMS.

As shown in Figure 7, the Z axis distance is directly provided by the vertical axis encoder, r is supplied by the horizontal axis encoder, and the angle ($\phi$) is supplied by the rotary axis encoder. Since the cylindrical coordinate system of the CMS is centered on the rotary bearing and/or encoder, offset corrections referencing the final coordinate values to the headboard related origins, i.e., $X_o$, $Y_o$, and $Z_o$ as shown in Figure 1, are incorporated into the software via the calibration procedure. The absolute accuracy of any axis may be checked at any time by direct measurement with a suitable caliper or depth gauge.

## Mechanical and Electrical Aspects

A simplified systems layout showing the connections of the subsystems of the AHD and its computer is given in Figure 8. Detailed drawings and a description of the individual components that comprise the mechanical parts of the CMS are provided in Appendix B. The electrical wiring diagrams for CMS are provided in Appendix C. As indicated, the encoders receive their power from the 5-V DC supply in the attached computer. Included with the diagrams in Appendix C is an illustration showing the component layout of the printed circuit board which contains the microchips for processing the encoder outputs and which must be installed in an expansion slot in the computer.

Because each of the component assemblies of the CMS contains sensitive instrumentation, they are designed to be independently removed and packaged for shipment. Special foam padded containers of fiberglass were constructed for this purpose. For detailed descriptions of the assembly, disassembly, and other practical matters related to the operation of the AHD, the reader is referred to the Operator's Instruction Manual in Appendix D.

## The Horizontal Axis Slide Assembly

The full horizontal axis slide assembly is shown in Figure 9. The basic structure is fabricated from aluminum stock and the complete assembly weighs approximately nine kg (20 lb). A mounting plate, located at the upper end of the arm, has two alignment pin holes to ensure proper positioning when mounted to the matching mounting plate surface on the vertical slide assembly. Four bolts are used to secure the arm in position. Associated with the slide are large control knobs or balls to assist the operator in positioning the touch probe. The active components of the assembly are shown in more detail in Figure 10.

The stainless steel slide bar is easily moved through a box-like structure that contains ball bearing plates on which the slide bar rides. The plate positions may be adjusted to reset the alignment. Teeth on the rack at the bottom of the slide bar drive the pinion gear attached to the shaft of the encoder causing it to rotate in accordance with the amount and direction of movement. The position of the encoder and its signal conditioner can be seen in Figure 10. The touch probe, which screws into the inner end of the slide bar, contains the ruby bead that contacts the point to be measured. When the AHD is properly calibrated, it is the center of this bead that reflects the coordinates being measured. The touch probe is a very sensitive and delicate switch, which may be automatically tripped by light contact of the bead with a

ABBREVIATIONS

A/M - Auto/Manual
BRK - Breaker
CSS - Chair Safety Stop
E - Encoder
GFI - Ground Fault Interrupter
"HP"- Head Positioned (Lights)
HSC - Head Stabilization Clamp
M - Motor
PCB - Printed Circuit Board
R - Relay
SC - Signal Conditioner
S/I - Stop/Interlock
TFR - Transformer
TP - Touch Probe

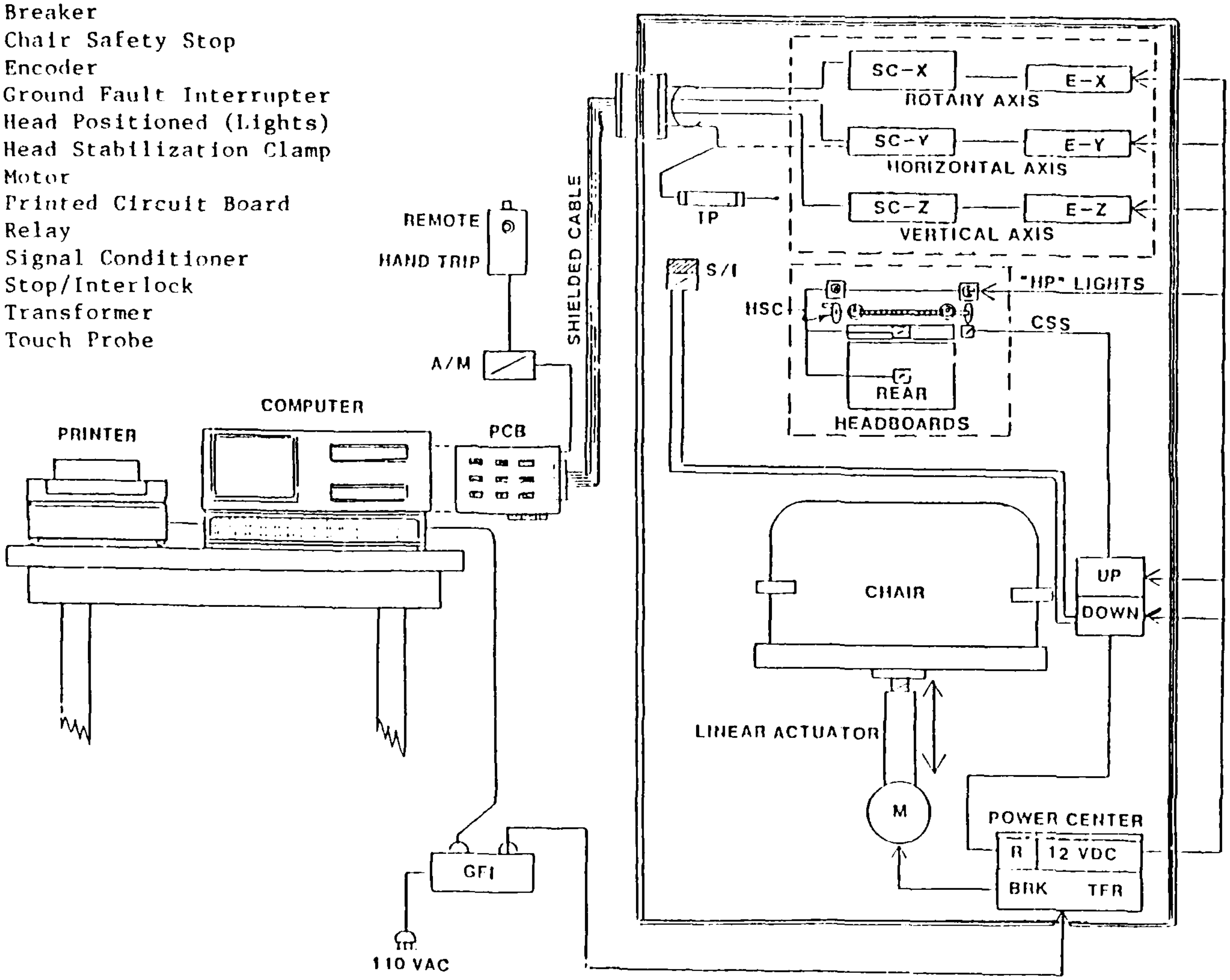



Figure 8. Systems layout for the AHD and its computer.

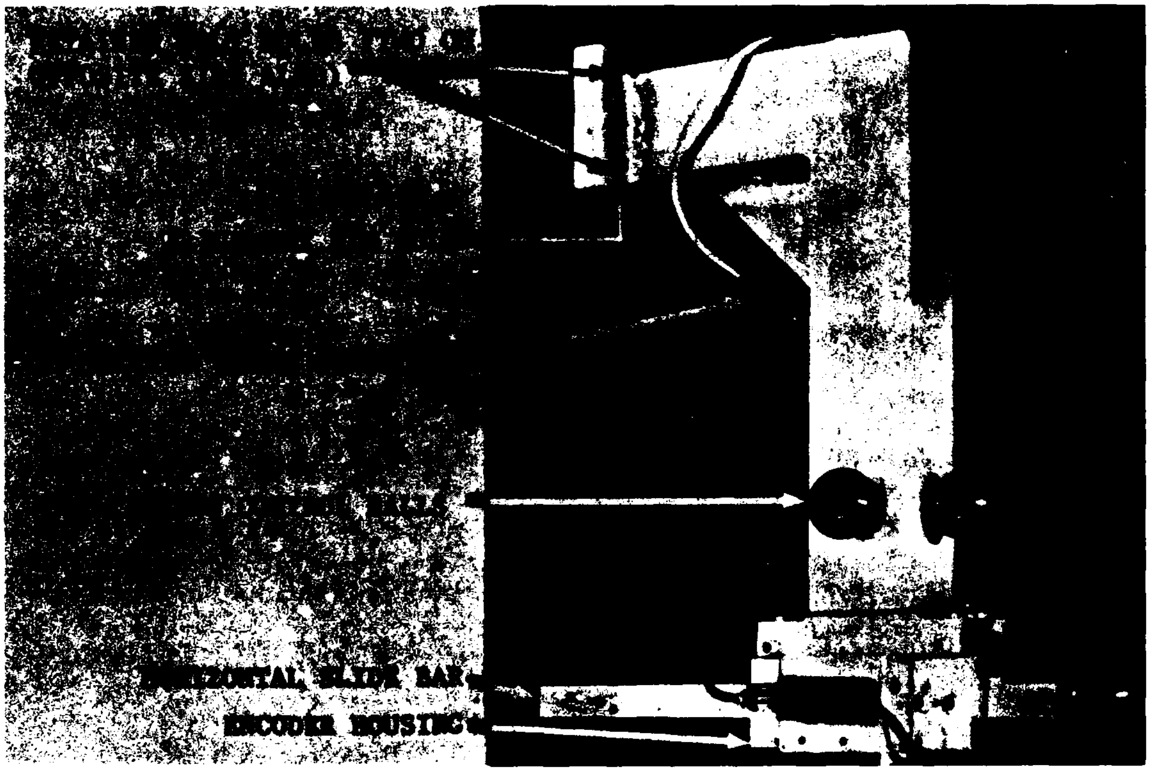


Figure 9. <u>The horizontal axis slide assembly and its mounting arm.</u>

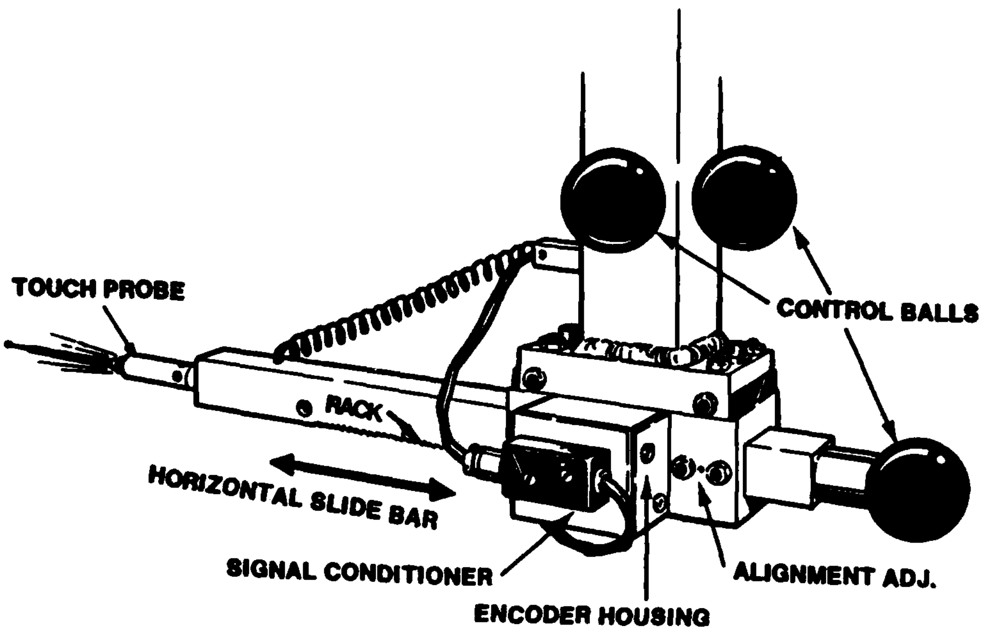



Figure 10. <u>Horizontal slide assembly.</u>

surface. Alternatively, points may be recorded by depressing a remote hand-activated switch (see Figure D-12). The stylus of the touch probe is moveable, minimizing the possibility of accidental injury to a subject.

## The Vertical Axis Slide Assembly

The vertical axis slide assembly is shown in Figure 11. The rather massive structure is constructed as a solid aluminum base upon which the horizontal axis arm is mounted. The entire assembly weighs nearly 14 kg (31 lb) and is in turn attached to and suspended from the rotary bearing. The massiveness of the structural aspects of the assemblies was required in order to secure the desired level of accuracy for the CMS. The mounting plate rides on the slide rails and, when not locked in position, permits the operator to raise and lower the attached horizontal axis arm as required to align the touch probe bead with the point being measured. Because the weight of the horizontal axis arm plus the mounting plate is substantial, it was necessary to counterbalance the combined parts in order to facilitate movement in the Z axis. The counterbalance spring indicated at the top of the assembly is attached to the rear of the mounting plate by a braided steel cable (aircraft type - 0.125" diameter, plastic coated).

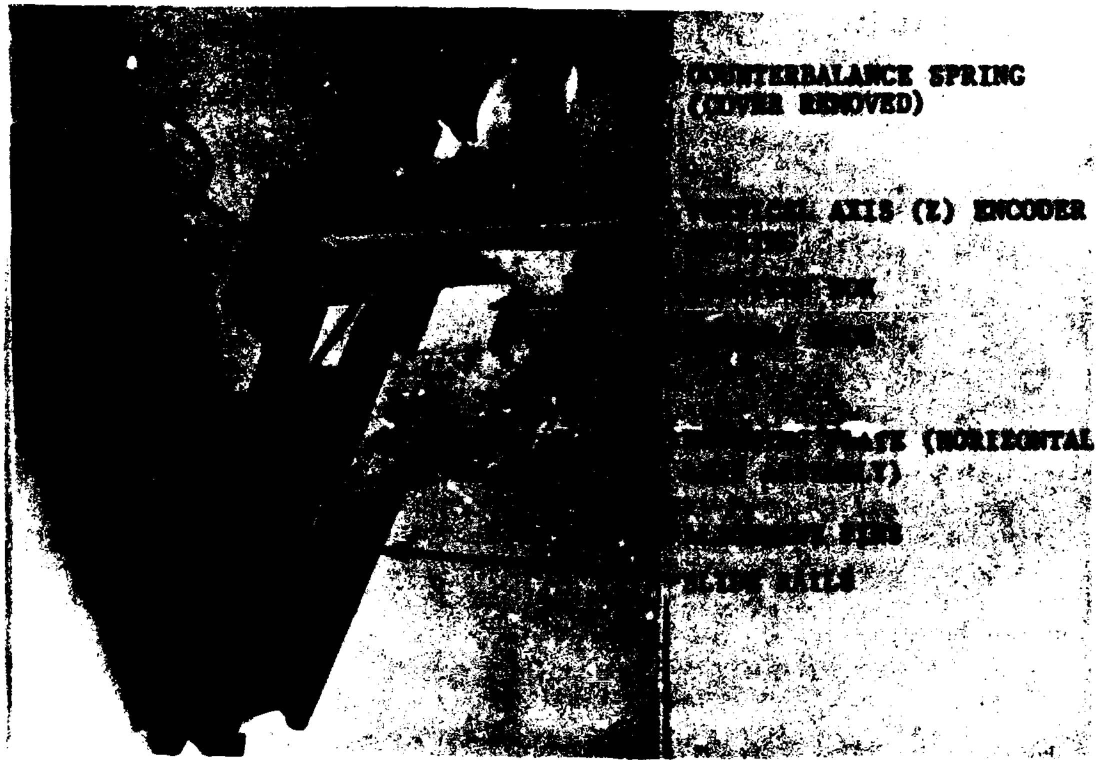



Figure 11. The vertical axis assembly.

The combined horizontal and vertical assemblies are mounted on the top of the rotary bearing using a right angle bracket attached to the rear of the vertical axis assembly. The assembly in position on the bearing is shown in Figure 12. The bottom plate of the bracket is secured to the bearing with four bolts located near the corners of the plate. As shown in the figure, two alignment posts are provided to assist in precisely positioning the plate.

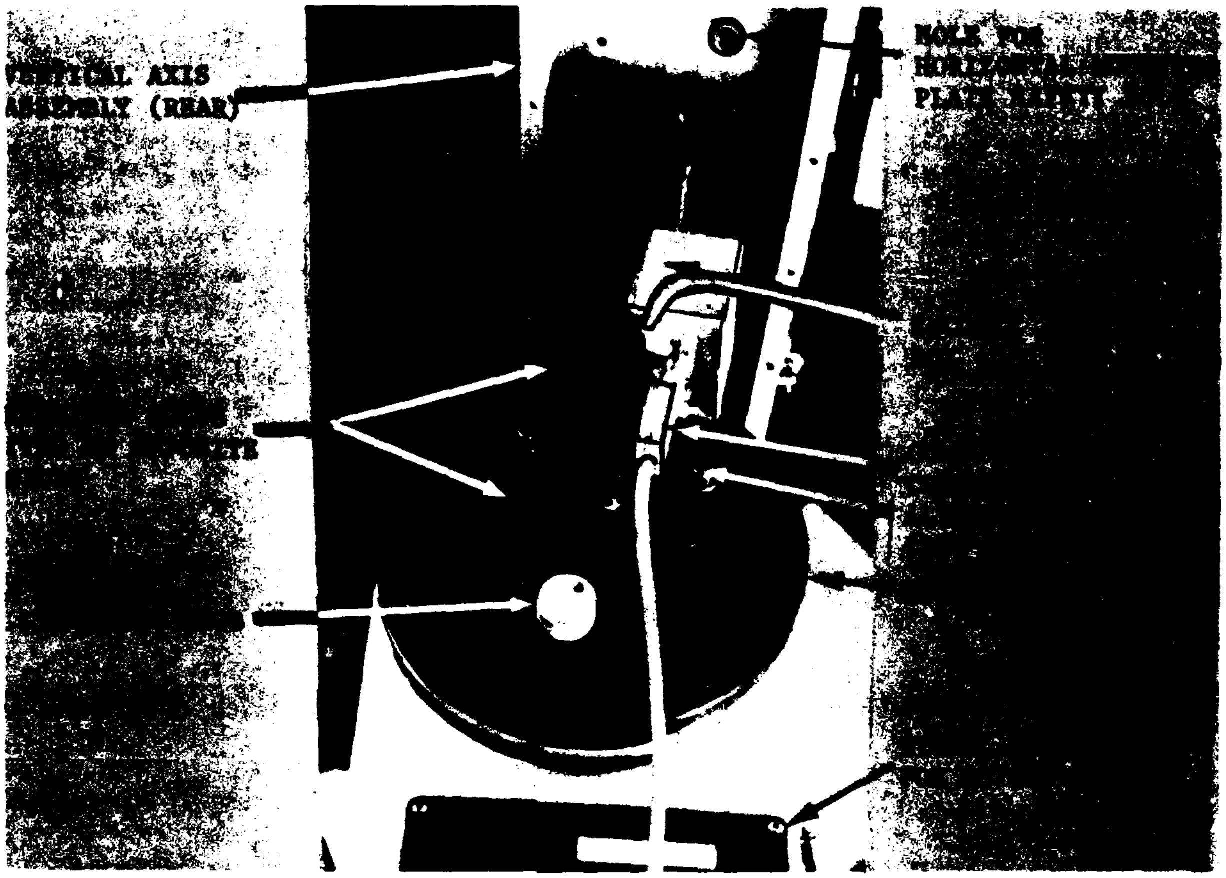


Figure 12. <u>The rotary bearing and the back of the vertical axis assembly viewed from above and behind</u>.

The horizontal mounting plate safety bolt was incorporated to secure the mounting plate during shipment and/or repair operations, when it was found that the vertical axis mounting plate could not always be held in position by its locking knob if jarred by impact. The double-threaded safety bolt is screwed into the mounting plate during dismantling for shipment and retracted during operation.

## The Rotary Axis

The rotary axis equipment consists of only two basic components -- the rotary bearing and its attached encoder. The large bearing sits atop the rounded support housing as shown in Figure 13. The encoder is coupled to the bearing by a central rotator shaft and is located within the support housing (not shown). The encoder, therefore, rotates exactly as the bearing rotates and provides the angular change (¢ in radians) around the CMS central axis when the arm is moved from point to point by the operator. Because strength, precision, and ease of rotation are necessary, the rotary bearing is quite rugged and rather complex in structure. The details of the structural components and their descriptions may be found in Appendix B. As shown in Figure 13, the bearing housing has mounted to it the alignment pins for the vertical axis assembly and a locking knob to hold the bearing (and the attached assembly) in a given position when not in use. The signal conditioner and counter for the rotary encoder is located just to the rear of the bearing and is mounted on the support housing. The job of the electronically complex signal conditioner is to shape and count pulses incoming from the encoder.

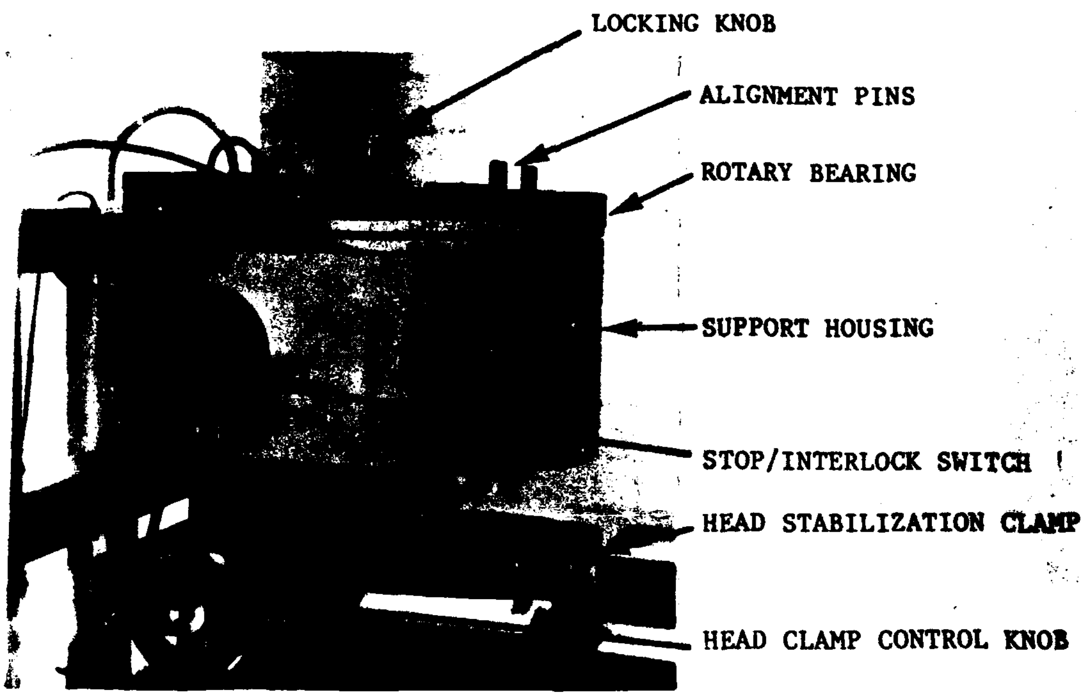



Figure 13. Rotary bearing and the support housing with the vertical axis assembly removed.

As noted previously, incoming signals from the three encoders are processed and coordinates are calculated by means of a special printed circuit board in combination with appropriate software incorporated in a compatible

computer. The software was specifically developed for the measurement of head and face coordinates in a format useful for analysis of the Army survey data. A copy of the program is provided in Appendix E of this report.

## THE SUBJECT POSITIONING SYSTEM (SPS)

The SPS includes those components of the AHD which are related to preparing a subject for measuring. The major components are the lift chair and its drive, the head positioning and stabilization equipment, and the associated controls. A list of component parts and a detailed chair assembly drawing appear in Appendix B. The electrical characteristics of the subject positioning system are given in the wiring diagram in Appendix C. All power for the system's components is supplied through the power center box located on the lower right rear of the support frame. For safety reasons, all components with which the subject may come in contact are powered by low voltage direct current (12 V DC) produced by a transformer/rectifier housed in the power center box. The only component of the entire AHD which uses 110 V AC power, as supplied by the standard three-pronged wall plug, is the chair drive motor. Use of a ground fault interrupter for the AC supply is recommended, although the system is protected by a 5-amp circuit breaker located in the power center box. Four "V" track wheels on the back of the chair support frame are used to guide the chair up and down the "V" tracks mounted on the AHD support frame (see Figure 14). The chair is equipped

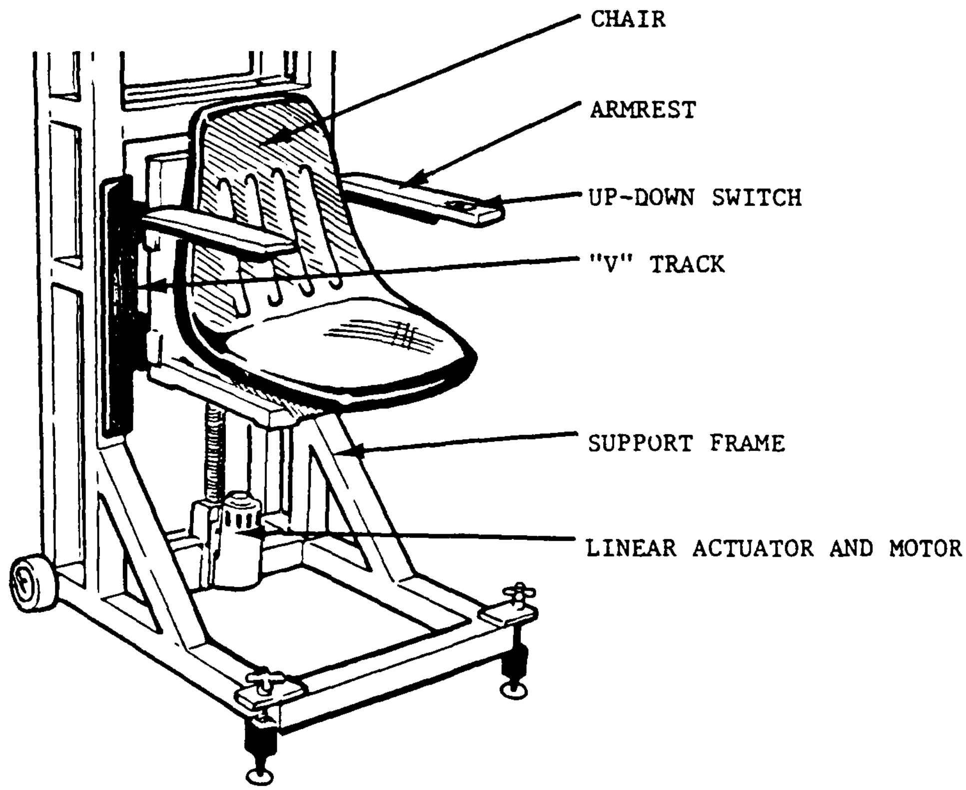



Figure 14. The positioning chair and its subassembly.

with armrests that may be pivoted upward for convenience during shipping and maintenance. Located in the armrest to the subject's left is a three-position rocker switch (UP-OFF-DOWN) which is used to control the drive motor. The motor can move the subject/chair combination up or down at the rate of 15 mm/sec (0.6 in/sec) over a distance of 30.5 cm (12.0 in).

The head positioning equipment is shown in Figures 15 and 16. The two headboard pieces are constructed of clear plastic and are hinged so that they must be pressed into a right angle configuration by the subject's head. Each piece is equipped with an adjustable stop so that the angle may be reset, if necessary. As the subject's head presses the headboards against their stops, two switches, which are wired in parallel, activate the "HEAD POSITIONED" lights on the rounded front of the support housing. The lights indicate to the operator that the subject's head is in firm contact with the two headboards and the headboards are positioned in a right angle configuration.


Figure 15. Head positioning equipment - front view.

Because head movement can be a source of error in measurement, a stabilization clamp was installed to minimize changes in position. The clamp is designed to contact the sides of the head above the ears. The clamp is opened (spread) and closed by the control wheel (see Figure 16) which turns a double-threaded shaft, causing the arms of the clamp to move equally toward or away from the system center line, i.e., center of rotation, rotary axis. As a result, the clamp not only helps to keep the head in the same position but also acts to center heads within the system during measurement.

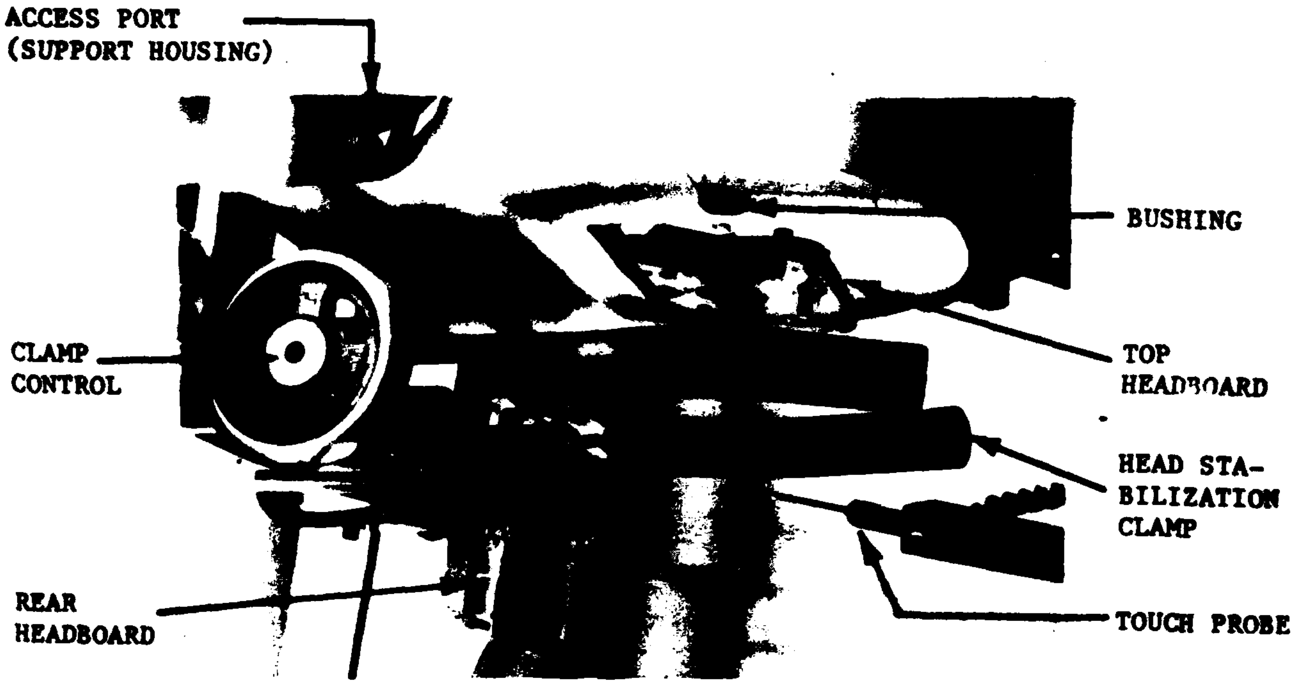



Figure 16. Head positioning equipment - side view.

Two switches, found just under the rotary support housing, are related to control of seat movement operations. One, the stop/interlock switch shown best in Figure 13, serves two functions: one is to act as a stop for the rotation of the CMS arm on the left side; the other to act as an interlock with the chair drive motor. The switch must be fully depressed by the CMS arm in order for the seat to be lowered. This control was installed as a safety measure to prevent a subject from leaving the chair when the CMS arm is in front of him/her. The function of the second switch is to automatically stop the chair from rising when the subject's head contacts and depresses the top headboard. This lever type switch is set to stop the chair just as the headboard approaches its right angle position. Without this control, there is a risk that a subject's head could be jammed against the top headboard by careless chair control, especially since it is usually the subject, and not an experienced operator, who controls the chair position.

## CALIBRATION TECHNIQUE

As noted, the CMS must "know" the exact 3-D location of the center of the touch probe bead at all points within its operational volume. In order to accomplish this, the software has a number of system constants built in. Among the constants which have been placed in memory are:

- the scale factors for the encoders, i.e., the number of counts/mm
- the location of the system's center of rotation in the XY plane relative to the surface of the rear headboard

These values are fixed. However, changes could be made by entering new values in the software. For example, for the 1987-1988 Army survey the scale factors are 50 counts/mm for the horizontal and vertical encoders and 111.11111 counts/mm for the rotary encoder. The system center of rotation is 88.1 mm forward of the rear headboard (X axis) and in the center of the Y axis (Y=0).

In order to compute coordinates, the CMS software requires that fixed and known distances and a known angle be put in by the calibration process. The X and Y axes are mutually interrelated to an angle ($\phi$) set in the rotary axis encoder and a fixed distance value (r) inputted by the horizontal axis encoder via the cosine and sine functions (see Figure 7). The Z axis calibration value is taken directly from a known distance inputted to the vertical axis encoder. Since the responses of the encoders are linearly related to distance change and the scale factors are built into the software, only a single accurately known value is needed to establish measurements along each axis. The actual steps taken by the operator in performing the calibration procedure are described in the operator's manual provided in Appendix D and will not be given here in detail.

The calibration procedure requires that the CMS arm be positioned in a fixed position when the system computer is turned on. This position is the BEGIN-END position in which the CMS arm is fully to the operator's left and tight against the stop/interlock switch. The $\phi$ angle at this point matches the one installed in the software. Although not important to the calibration itself, the horizontal slide is fully withdrawn against its stop and the vertical slide is locked against its upper stop. The fixed distances are factored into the system through the use of three pieces of calibration hardware. Two of the three components are threaded steel rods which are screwed finger tight into the bushings found on the bottom lateral aspect of the support housing (see Figure 17; see also Figures 15 and 16).

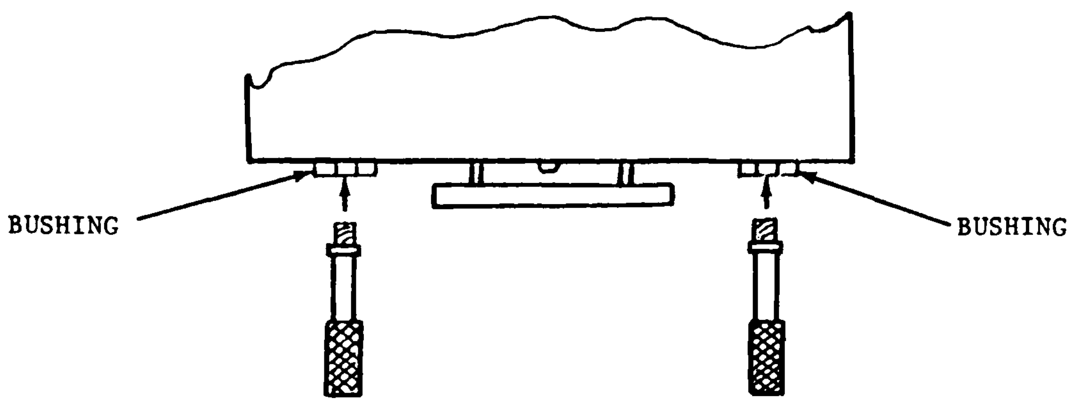



Figure 17. Support rods in position for installation in support housing.

The rods form the base to which the third component of the calibration hardware is attached. This component, called the calibration fixture or fixed radius fixture, provides fixed and repeatable surfaces from which known values for the needed distances may be inputted to the software. Basically, the fixture is constructed of two overlapping plates of aluminum 12.7 mm (0.5 in) thick. A top view of the fixture is shown in Figure 18. As can be seen, the top plate is machined with slotted cut-outs to fit the rods in a particular way. When in place, the fixture is secured so that its top surface is flush with the fully depressed upper headboard. The bottom plate of the fixture constitutes a portion of a precisely positioned circle of known diameter. When in calibration position, the center of the circle which has a diameter of 164.846 mm (6.490 in) is aligned with the center of the rotary axis of the CMS. Hence, the distance of the outer curved surface from the rear headboard is known -- 88.1 mm (headboard to center of rotary axis) + 82.423 mm (radius of fixture) = 170.523 mm. The installation and use of the fixture is more fully described in Appendix D. Briefly, two points, one taken at any place on the curvature and one from the bottom surface of the fixture, respectively, provide absolute set-points for the two distance values. Since the angle ($\phi$) at the point on the curvature is known from the BEGIN-END preset and the distance to the curvature (r) is known, the basic equations for X and Y are satisfied by their respective trigonometric relationships. The Z axis set-point comes from the fixture bottom touch point for which the distance from the top headboard surface is precisely known, i.e., 25.4 mm. As stated previously, this axis distance may then be directly computed without recourse to the X or Y information. The signs associated with the axis system are in the software. Figure 19 shows the calibration equipment installed.

## ANALYSIS OF ERRORS

Two major types of error apply to devices used by humans to measure human subjects: machine error and human error. In this case, machine error is associated with the sensitivity and repeatability of the encoders, the diameter of the touch probe tip, and the absolute accuracy of the calibration. Human error may be subdivided into operator error and subject-induced error. Typically, the two types of human error are combined as operator error, which is in turn added to the machine error to produce the total system error.

### MACHINE ERROR

As noted, the encoders are capable of resolving at least 0.05 mm. This level of sensitivity is approximately an order of magnitude better than that predicted for other error sources and should not contribute significantly to the total. The diameter of the bead and the calibration errors are interrelated since the system is calibrated to the center of the bead. The error associated with the calibration procedure relates to the accuracy with which the fixture can be positioned from one time to the next. Using height

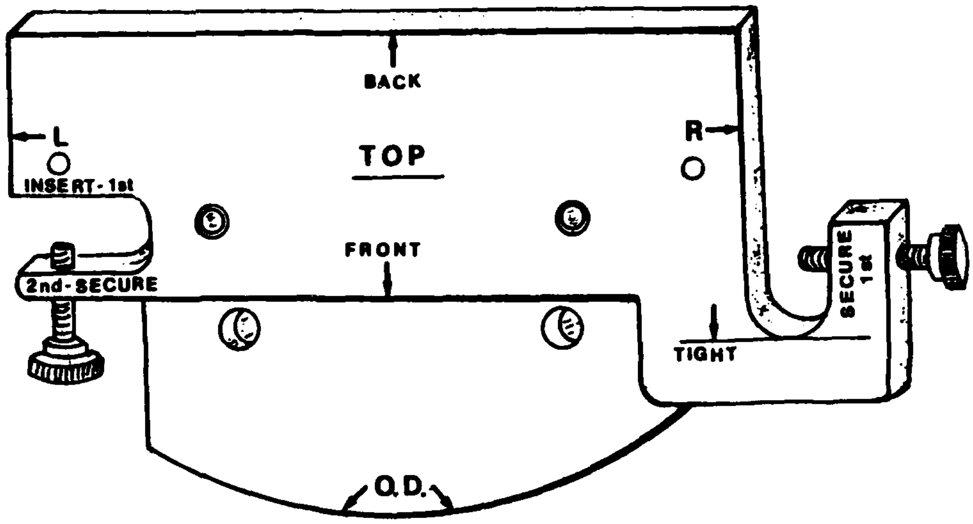



Figure 18. The fixed radius calibration fixture, top view showing labels.

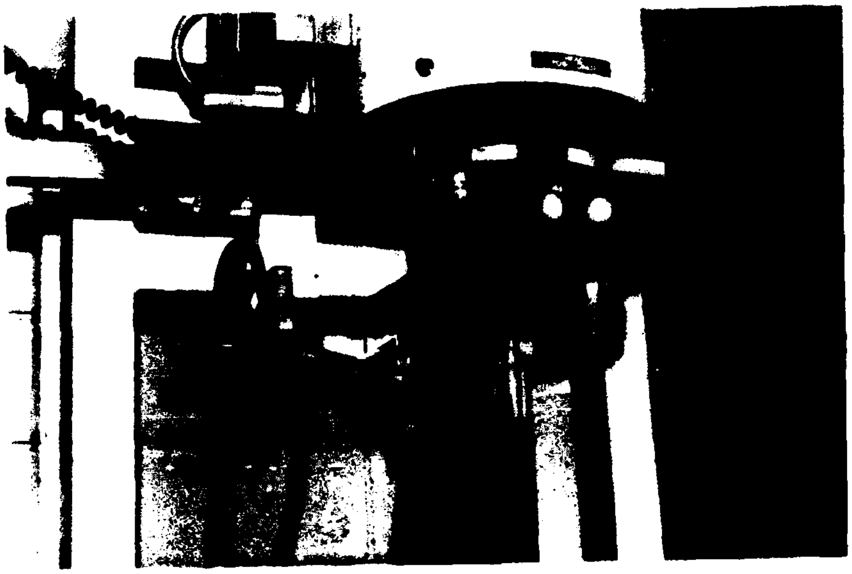


Figure 19. Calibration equipment in position on the AHD. (The support rods shown are an early version.)

gauges and calipers designed to 0.1 mm reading accuracy, it was determined that repositioning could be achieved easily to within 0.5 mm in all axes. Since the system is calibrated to the center of the touch probe bead, a potential maximum error in reading equivalent to the radius of the bead may be incorporated along any axis. For example, if the point being measured is touched by the outer edge of the bead, the center of the bead is displaced by a distance equal to its radius. Landmarks may be contacted at various points about the periphery of the bead, depending on the angle of incidence. The approach angle is set for each landmark by the machine but the angle of incidence varies with the size and shape of the subject's head and face at the point of contact. In order to establish reasonable corrections for such measurements, breadths derived from paired Y values in the AHD, and caliper-measured breadths for the same set of landmarks were compared. It was found that for live subjects the best overall correction for the more lateral of the landmarks required subtraction of one full bead radius regardless of machine/face geometry. Based upon the known and reasonably constant corrections needed for the midsagittal and near midsagittal landmarks, and the empirical finding for the more lateral landmarks, a list of corrections was developed for incorporation into the software so that on-line corrections could be made. The correction values used for the 26 different landmark locations measured in the 1987-1988 Army survey are listed in Table 2. Some error is known to remain, particularly for the bilateral landmarks; its magnitude, however, is quite small -- on the order of $\pm$ 0.1 mm.

## HUMAN ERROR

The operator error consists almost entirely of the potential variability in bead/landmark centering. In other words -- how well can a given operator position the bead on the drawn landmark? Variability in contact pressure and the resultant degree of tissue deformation when the coordinates are recorded is clearly the source of some additional error. Since the corrections for bead size are incorporated in the software, the measurement procedure for each location must be as prescribed or error will be incorporated in one axis or another. Fortunately, for almost all the landmarks listed, the operator will have few options from which to choose. Error can also, of course, be compounded by inaccurate landmarking.

Subject movement during measurement may also introduce errors. Shifting of the whole head or movement in areas of facial skin caused by expressional changes or muscular contraction can move most of the landmarks in 3-D space. Head movement has been minimized by the head stabilization clamp, although movement of the skin on the scalp cannot be entirely controlled. When bilateral landmarks are measured, severe errors may be introduced in the Y axis if side-to-side movements are in phase or out of phase with the order of measurement. For example, if the subject's head is positioned to some right extreme when a right side measurement is taken, and to some left extreme when a left side measurement is taken, the two errors are additive and the distance between them is much greater than a directly measured breadth at the two points. When the same movement is out of phase with the measurements (i.e., head to left when right is measured, and head to the right when the left point is measured), the indicated breadth is too small. Without knowledge of when and how much movement occurs in which axes, such errors cannot be corrected.

TABLE 2. Bead Offset Corrections for Landmarks Used in the 1987-1988 Army survey.

| Landmark | Correction* |
| --- | --- |
| R Tragion | Y + Bead Radius (r) |
| R Infraorbitale | X - Bead r |
| R Alare | Y + Bead r |
| R Cheilion | X - Bead r |
| R Gonion | Y + Bead r |
| R Zygion | Y + Bead r |
| R Ectoorbitale | X - 0.87 Bead r, Y + 0.5 Bead r |
| R Zygofrontale | Y + Bead r |
| R Frontotemporale | Y + Bead r |
| Crinion | X - Bead r |
| Glabella | X - Bead r |
| Sellion | X - Bead r |
| Pronasale | X - Bead r |
| Subnasale | X - Bead r |
| Stomion | X - Bead r |
| Promenton | X - Bead r |
| Menton | Z - Bead r |
| L Cheilion | X - Bead r |
| L Alare | Y - Bead r |
| L Gonion | Y - Bead r |
| L Tragion | Y - Bead r |
| L Zygion | Y - Bead r |
| L Infraorbitale | X - Bead r |
| L Ectoorbitale | X - 0.87 Bead r, Y - 0.5 Bead r |
| L Zygofrontale | Y - Bead r |
| L Frontotemporale | Y - Bead r |

* Since the X and Z indicated values are always positive, the corrections require subtraction of 1 bead radius, i.e. 1 mm. Depending on whether the Y location is right (Y is negative) or left (Y is positive) of the midline the bead radius is either added or subtracted from the indicated value. Except for the R/L Ectoorbitale landmarks, use of dual axes or trigonometric corrections proved to be unrewarding.

Some estimation of the magnitude for subject-induced error has been made in conjunction with the validation studies described in the last section of this report. The replication of the R Tragion and Sellion measurements (see Figure 3) were included to help indicate the magnitude of head movement across a measurement session and to assist in data editing decisions.

## COMPUTER HARDWARE AND SOFTWARE

The AHD was designed to operate in conjunction with a personal computer (PC) and software which processes the measurement data and produces a listing of coordinate values for individual head and face landmark locations. A typical example of a printout of the coordinate data for a subject is given in Table 3 where each value is given in millimeters. In the Army survey, the AHD was operated with a Compaq Portable II computer, equipped with a 80286 microprocessor, 640K RAM, dual 5¼-inch 360K diskette drives, and a full-sized expansion slot to accommodate the printed circuit board which receives, refines, and totals the signals from the encoders in preparation for the computation of the XYZ coordinate values. The operating system is MS-DOS Version 3.20. A diagram depicting the component layout of the printed circuit board is given in Appendix C (Figure C-3). Another PC compatible computer may be used with the AHD although its specifications should equal or exceed those noted above.

The main operating program was written using Turbo Pascal (version 3.01A, copyright 1985, Borland Inc., Scotts Valley, California). A copy of the program (printout) is included herein as Appendix E. This program allowed the operator to access various subroutines from a main menu. Included in the appropriate subroutines were the calibration constants, the software interface with the AHD printed circuit board, and the data recording and analysis procedures. A description of the menu items and their applications is given in the operator's instruction manual in Appendix D.

Among the features of the program are routines to individually rotate data sets according to a landmark-defined axis system. The rotation scheme was incorporated into the program after analysis of the validation test results showed that its use nearly halved the intra- and interobserver error. The axis system, and the effect of rotation on the error are described in the next section of this report.

Once rotated, an individual data set is examined via an edit routine which compares the measured value for each axis of each landmark against a value predicted by a multiple linear regression equation. If any measured value in a data set differs from its predicted value by more than $\pm$ 4 standard errors of the estimate, it is considered an error and the subject is remeasured. The partial regression coefficients were derived from the two predictor variables which showed the highest correlation with each axis of a given dependent variable. Since no true data base existed from which the regressions could be derived, the initial regression equations were computed from the data collected during the validation testing of the AHD. As additional data were collected, new and improved coefficients were periodically computed for installation into the edit routine.

TABLE 3. Sample Output of Coordinate Data.*

file : B:SN11263.YS

| | | | | |
|---|---|---|---|---|
| 1. | R. Tragion : | 99.9 | -67.9 | 129.2 |
| 2. | R. Infraorbitale : | 171.9 | -32.7 | 129.3 |
| 3. | R. Alare : | 184.8 | -16.6 | 154.4 |
| 4. | R. Cheilion : | 174.0 | -24.4 | 184.3 |
| 5. | R. Gonion : | 105.1 | -48.8 | 191.9 |
| 6. | R. Zygion : | 130.4 | -66.1 | 131.1 |
| 7. | R. Ectoorbitale : | 153.0 | -56.4 | 115.6 |
| 8. | R. Zygofrontale : | 160.1 | -54.4 | 101.4 |
| 9. | R. Frontotemporale : | 162.6 | -52.6 | 90.7 |
| 10. | Crinion : | 176.8 | 1.9 | 44.8 |
| 11. | Glabella : | 190.0 | -1.1 | 93.1 |
| 12. | Sellion : | 187.4 | 0.6 | 110.8 |
| 13. | Pronasale : | 211.6 | -1.8 | 151.4 |
| 14. | Subnasale : | 193.4 | -0.3 | 160.7 |
| 15. | Stomion : | 183.7 | 0.5 | 182.6 |
| 16. | Promenton : | 180.8 | 1.0 | 205.6 |
| 17. | Menton : | 168.8 | 2.3 | 221.2 |
| 18. | L. Cheilion : | 173.7 | 27.2 | 182.9 |
| 19. | L. Alare: | 191.3 | 13.5 | 152.5 |
| 20. | L. Gonion: | 101.1 | 53.6 | 182.4 |
| 21. | L. Tragion : | 99.6 | 67.2 | 126.7 |
| 22. | L. Zygion : | 121.9 | 65.9 | 129.7 |
| 23. | L. Infraorbitale : | 172.3 | 32.8 | 131.2 |
| 24. | L. Ectoorbitale : | 153.8 | 56.3 | 115.9 |
| 25. | L. Zygofrontale : | 156.2 | 54.8 | 106.2 |
| 26. | L. Frontotemporale : | 162.6 | 52.2 | 92.0 |
| 27. | Sellion : | 186.0 | 0.6 | 111.4 |
| 28. | R. Tragion : | 100.1 | -67.4 | 128.6 |

* Columns of numbers relate to the coordinate values for the X, Y, and Z axes (from left to right), respectively. Values are in millimeters.

## VALIDATION STUDY

Although the technology used in the CMS has been well tested on inanimate objects in industry, use with human subjects is new. So far as is known a rotary approach to coordinate measuring is also new. For these reasons, a series of validation tests was planned to determine whether the device could accurately and reliably measure head and face dimensions. Analyses include (1) inter- and intraobserver error tests of a wooden headform, (2) inter- and intraobserver error obtained from tests on human subjects, and (3) comparisons of measurements obtained from the AHD with measurements obtained from the traditional NATO headboard and some facial breadths obtained using standard anthropometric calipers. The following sections of the report provide a discussion of the preliminary studies performed, special analytical procedures used, the series of validation tests, and a summary analysis of the results. The numerous tables of data from which the summaries were derived and on which many of the conclusions are based are presented in Appendix F.

### PRELIMINARY STUDIES

Early in its development the CMS was exercised through a series of preliminary tests on both geometrically shaped objects of known dimensions and on live test subjects. Some of these trials were performed without appropriate calibrations and before construction of the head stabilization clamp; hence the data obtained during this time period are not included as part of the formal validation series reported below. Nevertheless, analysis of these early experiments provided encouragment for continued development of the device. Briefly, it was learned that the AHD could measure coordinates quite accurately when properly calibrated and operated. Data from inanimate objects indicated that an experienced operator could reliably reposition the touch probe bead on a given landmark with less than a 0.5 mm error in any axis. On the other hand, tests on living subjects indicated that positional differences, soft tissue effects, and random head movements could produce sizable errors in coordinates for a given landmark. Such errors have most probably been associated with NATO headboard data; however, so far as is known, no analysis of the magnitude of error incurred has been published. In the current study, repeat tests occasionally showed variations from 1 to 2 cm in landmark position for one axis or another when heads were unrestrained in the AHD or placed normally in the NATO headboard. While none of the sources of error can be totally eliminated, use of the head stabilization clamp considerably reduced the variations caused by movement in the early AHD trials. A computer program which rotates entire data sets to a landmark-based axis system was developed to reduce the error due to variations in head orientation. To facilitate analysis of the AHD data, a mathematical expression was used which permits presentation of the difference in location of two sets of 3-D coordinates as a single distance value. The experiments, the analytical techniques used, and the results of the validation study are discussed in more detail below.

## TREATMENT OF THE DATA

### Data Rotation

Preliminary studies with the AHD indicated that despite all efforts to standardize the position of the subjects' heads, substantial error in coordinate measurement could result from orientational differences between tests on the same subject or between different subjects. In order to minimize this source of error, a computer program was developed which permits rotation of entire data sets to a new axis system defined by three landmark locations measured during the test. The axis system used as the basis of the rotation is depicted in Figure 20.

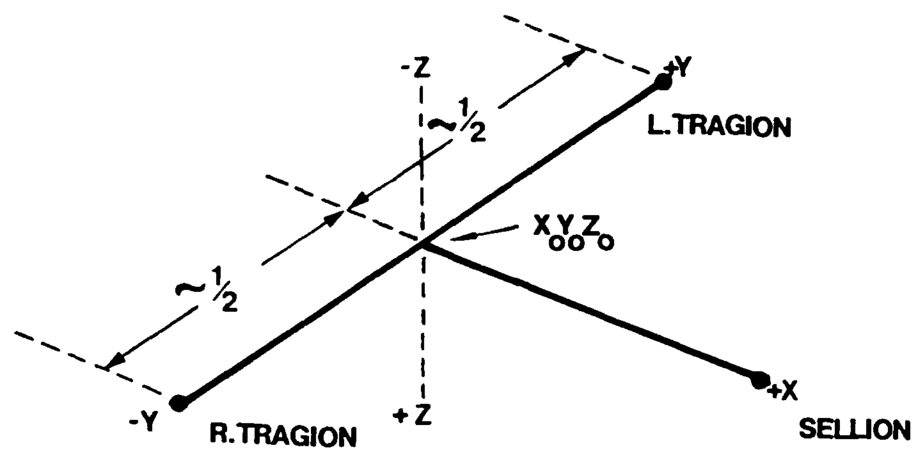



Figure 20. Axis system used as the basis for rotation.

Through the use of the rotation routine, the need for precise positioning of each subject's head becomes less critical, since the data for all individuals in a given sample can be rotated into exactly the same orientation. It will be noted from Figure 20 that the rotation scheme used the right and left tragion to establish the Y axis. The X axis is keyed to sellion and projected perpendicularly from the Y axis. The Z axis is positioned orthogonally at the XY intersect to establish the origin ($X_oY_oZ_o$) for the system. As indicated in the illustration, the zero point is typically near the midpoint on the bitragion line.

Comparisons of rotated and non-rotated data (see Appendix F, Table F-9) show that rotation virtually cuts in half both intra- and interobserver differences caused by variations in head position. Use of this technique eliminates the need to position subjects' heads in the true Frankfort plane; however, for consistency in the data and to avoid editing flags we continue to orient heads as nearly as possible in the Frankfort plane before applying the stabilization clamp.

Calculation of 3-D Distances

While it is possible to examine observer error along each axis individually, this is both cumbersome analytically and not a good representation of how observer differences occur. Two observers locating the same point are likely to be different from each other in some combination of the three axes, not just in one. Since the error itself is a combination of all three axes, we have analyzed the error data with all axes examined simultaneously. This is done by calculating the distance, in 3-D space, between two points. Each of those points represents one attempt to establish the 3-D coordinates for a given landmark. For example, if we have the landmark R Tragion, and two observers use the AHD to obtain its coordinates, then we have two sets of XYZ values. The distance, in space, between those two points is the (inter-) observer error. That distance (d) is calculated by an expansion of the Pythagorean Theorem as follows:

$$d = \sqrt{(X_1-X_2)^2 + (Y_1-Y_2)^2 + (Z_1-Z_2)^2}$$

where d = the distance in space between two points, whose coordinates are $X_1Y_1Z_1$ and $X_2Y_2Z_2$:

$X_1-X_2$ = difference in X for trial 1 and trial 2 (intraobserver) or observer 1 and observer 2 (interobserver).

$Y_1-Y_2$ = difference in Y for trial 1 and trial 2 (intraobserver) or observer 1 and observer 2 (interobserver).

$Z_1-Z_2$ = difference in Z for trial 1 and trial 2 (intraobserver) or observer 1 and observer 2 (interobserver).

The magnitude of the distance is always at least as large as the largest of the differences observed when the axes are compared independently. The replicability in the Z axis was generally somewhat poorer than in X or Y, but this was attributed to the fact that movements of the vertical slide mechanism (Z axis) were somewhat more difficult to perform than the rotation of the arm and movement of the horizontal slide (X and Y axes).

## THE VALIDATION TEST SERIES

Four anthropometrists acted as measurers in the validation tests. Each was experienced in traditional head and face measurement techniques, and had received training in the operation of the AHD prior to the test series. The "subjects" included a wooden headform and 10 volunteers -- 3 men and 7 women -- drawn from the staff of Anthropology

Research Project. The wooden headform was measured twice by each investigator on the AHD, and four times by one investigator on the NATO headboard. Each live subject was run through the complete AHD measurement sequence two times by each operator, for a total of 80 (10 x 4 x 2) tests. During the same measuring session, six subjects from this group were also measured twice by two anthropometrists (observer #1 and observer #2) in the NATO headboard for a total of 24 (6 x 2 x 2) tests. The AHD and the NATO headboard measurements utilized the same set of drawn landmarks. Since only lengths (Z axis) and depths (X axis) are obtained on the NATO headboard, a group of nine facial breadths were also measured using standard anthropometric calipers in order to provide an independent check of the Y axis measurements by the AHD. The caliper measured breadths and their associated landmarks are listed below:

| Breadths | Landmarks: From - To |
|---|---|
| Minimum Frontal | R Frontotemporale - L Frontotemporale |
| Maximum Frontal | R Zygofrontale - L Zygofrontale |
| Biectoorbitale | R Ectoorbitale - L Ectoorbitale |
| Biinfraorbitale | R Infraorbitale - L Infraorbitale |
| Bitragion | R Tragion - L Tragion |
| Bizygomatic | R Zygion - L Zygion |
| Bigonial | R Gonion - L Gonion |
| Nose | R Alare - L Alare |
| Lip (Length) | R Cheilion - L Cheilion |

## AHD Measurements

Landmarks for the 26 points measured on the AHD (see Figure 3) were drawn on all subjects by one investigator, and the targets positioned on the wooden headform by another. A detailed description of the measuring procedure used with the AHD appears in the operator's manual in Appendix D. In these validation trials, subjects were removed from the AHD chair and completely repositioned between measurements. All points were recorded using the remote hand switch rather than the "auto trip" mode for the touch probe, since it had been determined earlier that the pressure required for the "auto-trip" method caused depression of the soft tissue underlying many of the landmarks. The manual technique permitted the operators to instruct their computer operator assistants to record the point just as the skin was touched or visibly dimpled by the touch probe bead. The manual-trip method was also used throughout the 1987-88 U.S. Army Survey.

During the validation test series the AHD was functionally complete, although several operational procedures used were different from those described in the operator's instruction manual in Appendix D. For example, at the time of the tests, the chair control switch had not yet been installed in the right armrest; hence the originally supplied hand held switchbox was used by the subjects to raise themselves into position. We found that, especially for the shorter subjects, a foot support was useful in promoting comfort and stability during measurement. A ten-inch-high stool from the laboratory was used for the validation tests. Later a custom designed stool was built of plywood for field use.

Since the calibration fixture and its associated software were not completed at the time of the validation testing, calibrations were based upon values obtained by direct measurement of the bead center when the arm and slides of the CMS were locked in a fixed, stable position. With the arm positioned in the exact center of its range of rotation, i.e., when the horizontal slide is perpendicular to the plane of the rear headboard (Y = 0), the distance of the bead center to the top headboard (Z axis distance) and to the rear headboard (the X axis distance) was measured with a height gauge to the nearest 0.5 mm. The XYZ values obtained were put into the computer in much the same way as it is done with the calibration fixture. Any location of the bead in the X or Z axis could be used since the scaling factors were already in the software and the distance from the center of rotation to the rear headboard was known. Typically, following this type of calibration sequence, the bead was randomly moved about within the range of operation and checked for "absolute" accuracy using the same height gauge. The on-line printouts looked like the sample given in Table 3 since the special treatments of the data described above were performed subsequent to the experiments.

### NATO Headboard Measurements

A height gauge was used to measure lengths and depths from the same set of drawn landmarks used in the AHD tests; the data were manually recorded by the assistant. In order to lessen the stress on the six subjects measured in both conditions, bilateral landmarks were sampled only on the right side during the NATO headboard measurements, as traditionally done in previous surveys. As a result, 17 landmark locations were measured in this test series. In the past, most headboard measurements have been taken from standing subjects. However, in this case, subjects were seated for measurement to better simulate the AHD measurement conditions.

### Results

Because of the complexity of 3-D data, the lack of direct comparability of the methods of measurement employed, and the relatively small test samples, the analyses of results were generally restricted to comparisons of simple means for the intraobserver and interobserver differences. Where feasible, comparisons of techniques were made. Generally, mean values for the differences observed in each variable for each comparable condition were calculated. Grand means were also computed in some cases in order to provide summary data which are easier to examine. Such summary analyses are presented below; however, the reader who wishes to examine a more detailed presentation of the validation findings is referred to Appendix F.

**Wooden Headform.** Use of the wooden headform, which served as the inanimate test object in the series, permitted assessment of an individual operator's ability to position or reposition the touch probe of the AHD on each of the 26 landmarks under conditions of absolute stability of surface, as well as of the entire test object. As such, the headform is free of error introduced by movement and by the compression of soft tissue associated with the live test data. Since the same advantages accrue to use of the headform as a "subject" for traditional measurements, the headform data reflect in

more absolute ways than do the data of live subjects the reliability of the AHD as a measurement instrument. The same benefits apply, of course, when measuring the headform in the NATO headboard.

A summary of the intraobserver and interobserver error obtained in the eight AHD tests of the wooden headform is presented in Table 4 (see also Appendix F, Tables F-3 and F-4). The reader is reminded here that "error" in this context means the distance in three-dimensional space between two sets of coordinates which represent a first and second attempt to measure the same point. The intraobserver data indicate that, on the average (grand mean), for all landmarks, operators were able to reposition the probe within 0.61 mm in 3-D space. The comparable data for the axes individually were 0.23 mm, 0.24 mm, and 0.44 mm for X, Y, and Z, respectively (see Appendix F, Table F-1). The magnitude of the errors ranged from 0.0 for L Infraorbitale to 2.3 mm for L Cheilion; there are too few replications to speculate meaningfully about why it was more difficult to achieve replicability for some landmarks, if indeed there is a discernable pattern. As noted on Table 4, analysis disclosed that the AHD operators had used a somewhat different probe positioning technique for the Subnasale landmark; however, each operator was internally consistent.

The headform data sets were not rotated. Because a sizable orientation difference went undetected when the headform was removed and replaced in the AHD between the two sets of tests performed by operators #1 and #2 and the two sets of tests run by operators #3 and #4, the analysis of the interobserver error presented in Table 4 was limited to two of the six possible combinations. Assuming that the two sets of data compared in the table are representative, the data indicate that the error between operators is generally only slightly greater, on the average, than the intraobserver error. This suggests that little is sacrificed in accuracy when measurements are performed by different operators with similar skills. For interobserver tests, the average absolute error observed for each axis independently for the same data sets were determined to be 0.29 mm, 0.25 mm, and 0.54 mm for X, Y, and Z, respectively (see Appendix F, Table F-2).

As noted previously, the headform was also measured in the NATO headboard. Because the wooden headform data were never rotated, it was thought that differences in head orientation would be so great as to preclude a direct comparison of the two methods. Upon examination of the data however, it was found that orientation of the wooden form in the NATO headboard was apparently very similar to that achieved by operators #3 and #4 on the AHD. It was found that the two methods showed average absolute differences of 2.19 mm and 1.12 mm for the X and Z axes, respectively. These data are presented more fully in Appendix F, Table F-5. Considering that some orientation differences did exist in the two conditions (due to repositioning between trials and difficulties encountered in propping or clamping the headform in the Frankfort plane position), and considering further that actual unrotated measurement values were used to derive the differences, one may conclude that the measurement techniques are comparable.

TABLE 4. Summary of Intra- and Interobserver Error for the Wooden Headform Measured in the AHD (points not rotated; 3-D distance values in mm).

| Landmark | INTRAOBSERVER ERROR For 4 Observers Trial #1 vs. Trial #2 Range | Mean | INTEROBSERVER ERROR Obs #1 vs. #2 and Obs #3 vs. #4 All Trials Range | Mean |
|---|---|---|---|---|
| R Tragion | 0.4 - 0.6 | 0.5 | 0.2 - 0.8 | 0.5 |
| R Infraorbitale | 0.1 - 1.5 | 0.8 | 0.5 - 1.5 | 0.9 |
| R Alare | 0.1 - 0.7 | 0.3 | 0.1 - 1.6 | 0.9 |
| R Cheilion | 0.3 - 1.0 | 0.5 | 0.4 - 0.7 | 0.6 |
| R Gonion | 0.4 - 0.9 | 0.7 | 0.1 - 0.9 | 0.5 |
| R Zygion | 0.5 - 1.1 | 0.7 | 0.8 - 1.2 | 0.9 |
| R Ectoorbitale | 0.3 - 1.6 | 0.7 | 0.3 - 1.4 | 0.8 |
| R Zygofrontale | 0.4 - 0.7 | 0.6 | 0.3 - 0.7 | 0.5 |
| R Frontotemporale | 0.4 - 0.7 | 0.6 | 0.3 - 0.5 | 0.4 |
| Crinion | 0.3 - 0.7 | 0.4 | 0.2 - 0.6 | 0.4 |
| Glabella | 0.4 - 0.9 | 0.6 | 0.4 - 1.0 | 0.6 |
| Sellion | 0.4 - 1.1 | 0.7 | 0.5 - 1.1 | 0.8 |
| Pronasale | 0.3 - 0.9 | 0.7 | 0.2 - 1.0 | 0.6 |
| Subnasale | 0.2 - 0.8 | 0.5 | 1.5 - 3.0* | 2.3* |
| Stomion | 0.5 - 1.0 | 0.8 | 0.6 - 1.7 | 1.2 |
| Promenton | 0.1 - 0.5 | 0.3 | 0.1 - 1.1 | 0.5 |
| Menton | 0.2 - 1.7 | 0.7 | 0.5 - 3.0 | 1.6 |

* Reflects procedural difference in measurement (see Table F-4).

TABLE 4. Continued

| Landmark | INTRAOBSERVER ERROR For 4 Observers **Trial #1 vs. Trial #2** Range | Mean | INTEROBSERVER ERROR Obs #1 vs. #2 and Obs #3 vs. #4 **All Trials** Range | Mean |
|---|---|---|---|---|
| L Cheilion | 0.2 - 2.3 | 1.0 | 0.2 - 1.8 | 0.8 |
| L Alare | 0.5 - 1.6 | 0.9 | 0.1 - 2.1 | 0.7 |
| L Gonion | 0.1 - 1.0 | 0.7 | 0.4 - 0.9 | 0.7 |
| L Tragion | 0.1 - 0.9 | 0.5 | 0.2 - 1.4 | 0.7 |
| L Zygion | 0.4 - 0.6 | 0.5 | 0.6 - 0.9 | 0.7 |
| L Infraorbitale | 0.0 - 0.6 | 0.3 | 0.1 - 0.6 | 0.3 |
| L Ectoorbitale | 0.4 - 0.5 | 0.5 | 0.4 - 1.3 | 0.7 |
| L Zygofrontale | 0.1 - 1.5 | 0.7 | 0.1 - 0.8 | 0.5 |
| L Frontotemporale | 0.4 - 1.1 | 0.8 | 0.4 - 1.0 | 0.6 |
| (repeats) | | | | |
| Sellion | 0.2 - 0.4 | 0.3 | 0.4 - 1.1 | 0.6 |
| R Tragion | 0.1 - 1.3 | 0.7 | 0.2 - 0.9 | 0.5 |
| GRAND MEANS ALL LANDMARKS | 0.28-1.01 | 0.61 | 0.36-1.24 | 0.74 |

Using data from trial #1 for each AHD operator, an average breadth for the bilateral landmarks was calculated (i.e., using the "d" formula and XYZ values from each of the bilateral landmarks) for comparison with breadths that were directly measured with anthropometric calipers on several occasions by the same operator. For the eight breadths that were measured comparably, the average absolute difference in the two techniques was slightly over 1.0 mm. The largest individual difference observed was 2.0 mm (see Appendix F, Table F-6). Taken altogether, the wooden headform tests appear to demonstrate that the AHD repeatably measures distances in all three axes.

**Test Subjects.** Summarized results for the 10 live subjects measured in the AHD are presented in Table 5. The table gives the range and the mean intra- and interobserver error for each of the 26 landmarks (plus repeats) as measured by the four operators.

Overall, the intraobserver data indicate that for all landmarks the operators were able to reposition the touch probe within an average of slightly less than 2 mm. Individually, for the measured points, the operators were able to relocate the points within a maximum distance of 3.6 mm (R Gonion). It is interesting to note that of the variables, Sellion appears to be the most reliably measured since all operators were able to relocate the point within 0.8 mm. At the other extreme, the most difficult landmarks to measure appear to be Gonion (R and L), Crinion, Cheilion and Menton. When viewed in terms of the range of variability for the four operators, those landmarks which demonstrated a 1.0-mm range or greater include R Infraorbitale, R Gonion, Crinion, Stomion and L Cheilion. The mean distance between replications for each individual operator are given on Table F-7 in Appendix F.

The range and mean distance between points for all of the six possible interobserver combinations in a single trial are also given in Table 5. The data for operator pairs individually are presented in Appendix F, Table F-8. Trial 2 results, though not presented, were similar. In general, the data indicate that the four investigators were nearly as good at replicating each other as they were in replicating themselves. The grand mean distance for all landmarks and all six operator pairs was 2.09 mm or only 0.18 mm greater than for the intraobserver grand mean. It is not surprising that the same landmarks appear to be more or less reliable for both intra- and interobserver error and that the grand mean error for the interobserver analysis is similar in magnitude to that for the intraobserver analysis.

Immediately following their tests in the AHD, six test subjects were measured twice each in the NATO headboard by two observers. These results are presented in Appendix F. In general, both measurers were somewhat better in measuring in the X axis than in the Z axis direction. This is perhaps due to the rather awkward hand positions required when measuring from the top headboard. The two observers were nearly twice as good at replicating themselves as they were in replicating each other. In both types of comparisons the differences for a given landmark or on the average for all landmarks were greatly influenced by rather large (up to 2 cm) changes in head position between or during the tests. The error tended to increase with the length of time the subject was asked to remain motionless, since the larger differences are generally associated with the last variables measured in each axis.

TABLE 5. Summary of Intra- and Interobserver Error for Ten Test Subjects Measured in the AHD (rotated points; 3-D distance values in mm).

| | INTRAOBSERVER ERROR 4 Observers **Trial #1 vs. Trial #2** | | INTEROBSERVER ERROR 6 Comparisons 4 Observers **For Trial #1 Only** | |
|---|---|---|---|---|
| Landmark | Range | Mean | Range | Mean |
| R Tragion | 1.3 - 1.9 | 1.6 | 0.9 - 1.8 | 1.5 |
| R Infraorbitale | 1.1 - 2.4 | 1.7 | 1.5 - 2.3 | 1.9 |
| R Alare | 1.1 - 1.7 | 1.4 | 1.4 - 1.6 | 1.5 |
| R Cheilion | 1.7 - 2.0 | 1.9 | 2.2 - 3.2 | 2.8 |
| R Gonion | 2.0 - 3.6 | 2.7 | 2.1 - 3.4 | 2.8 |
| R Zygion | 1.6 - 2.3 | 2.1 | 1.6 - 2.5 | 2.1 |
| R Ectoorbitale | 1.5 - 2.1 | 1.8 | 1.8 - 2.5 | 2.2 |
| R Zygofrontale | 1.2 - 1.9 | 1.6 | 1.5 - 2.2 | 1.8 |
| R Frontotemporale | 1.5 - 2.2 | 1.9 | 1.1 - 2.1 | 1.6 |
| Crinion | 2.1 - 3.2 | 2.6 | 2.5 - 3.2 | 3.1† |
| Glabella | 1.4 - 1.9 | 1.6 | 1.5 - 1.7 | 1.6 |
| Sellion | 0.8 - 0.8 | 0.8 | 0.5 - 1.4 | 1.2 |
| Pronasale | 1.0 - 1.4 | 1.2† | 1.1 - 1.4 | 1.2† |
| Subnasale | 1.4 - 1.9 | 1.6† | 1.4 - 2.2 | 1.9 |
| Stomion | 1.8 - 2.8 | 2.2† | 2.0 - 3.2 | 2.7 |
| Promenton | 2.0 - 2.5 | 2.3† | 2.2 - 2.8 | 2.4† |
| Menton | 2.5 - 2.9 | 2.7† | 2.3 - 3.3 | 2.8 |

† These means and ranges exclude apparent errors in one or more files due to mismeasurement or faulty sequencing of points. See Table F-7 (intraobserver) and Table F-8 (interobserver) for excluded values.

TABLE 5. Continued

| Landmark | INTRAOBSERVER ERROR 4 Observers **Trial #1 vs. Trial #2** Range | Mean | INTEROBSERVER ERROR 6 Comparisons 4 Observers **For Trial #1 Only** Range | Mean |
|---|---|---|---|---|
| L Cheilion | 2.2 - 3.3 | 2.7† | 2.5 - 3.2 | 3.1 |
| L Alare | 1.7 - 2.2 | 2.0 | 1.5 - 2.7 | 2.2 |
| L Gonion | 2.5 - 3.1 | 2.7 | 2.2 - 2.6 | 2.5 |
| L Tragion | 1.0 - 1.5 | 1.3 | 0.8 - 1.6 | 1.2 |
| L Zygion | 1.7 - 2.3 | 2.0 | 1.8 - 2.3 | 2.1 |
| L Infraorbitale | 1.3 - 1.9 | 1.7 | 1.3 - 2.0 | 1.8 |
| L Ectoorbitale | 1.8 - 2.4 | 2.0 | 1.6 - 2.2 | 1.9† |
| L Zygofrontale | 1.6 - 2.2 | 1.8 | 1.6 - 2.1 | 1.8 |
| L Frontotemporale | 1.8 - 2.1 | 1.9* | 1.9 - 2.9 | 2.4 |
| (repeats) | | | | |
| Sellion | 1.2 - 2.0 | 1.6* | 1.8 - 2.5 | 2.1 |
| R Tragion | 1.9 - 2.4 | 2.1* | 1.5 - 2.9 | 2.2 |
| GRAND MEANS | 1.60-2.25 | 1.91 | 1.65-2.42 | 2.09 |

* Missing data; see Table F-7, Observer #3.

It is clear from the foregoing analyses that the repeatability obtained with the AHD is better than that for the NATO headboard measurements. A summary of the mean absolute difference in 17 landmark locations in the X and Z axes for the six subjects measured by observers #1 and #2 in both headboards is presented in Appendix F, Table F-12. The grand mean difference for all landmarks in both axes was approximately 4.0 millimeters for the two procedures. In general, the agreement obtained by observer #1 was somewhat better than that for observer #2 and somewhat better for the X axis than the Z axis in both cases.

Since the "d" values determined for the AHD tests must be at least as great as the difference in distance for any single axis, a comparison of the grand mean differences (first 17 landmarks) for the two methods can be made. The following intraobserver data, summarized from Tables F-7 and F-10, are obtained for the six subjects tested.

Intraobserver Data -- Table F-7, F-10

| OBSERVER 1 | | OBSERVER 2 | |
|---|---|---|---|
| Trial 1 vs. Trial 2 | | Trial 1 vs. Trial 2 | |
| **AHD** | **NATO** | **AHD** | **NATO** |
| "d" = 1.89 mm | X = 2.81 mm | "d" = 1.79 mm | X = 3.12 mm |
| | Z = 2.78 mm | | Z = 4.08 mm |

Interobserver data, summarized from Table F-8 and F-11, are shown below:

OBSERVER 1 vs. OBSERVER 2
(TRIAL 1)

| AHD | NATO |
|---|---|
| "d" = 1.96 mm | X = 4.83 mm |
| | Z = 6.31 mm |

As can be seen, errors obtained by using the NATO headboard were from one-and-a-half to three times as high as those obtained in the AHD tests, although the NATO headboard data would doubtless have been improved if rotation of the data sets could have been performed.

A summary of the average differences obtained for caliper-measured and AHD-measured breadths is shown in Appendix F, Table F-13. In most cases breadths derived from the AHD coordinates were larger than breadths measured with calipers. The largest net differences were for bigonial breadth. It was suspected that most of the difference was due to caliper compression of the extremely soft tissue in the area of the gonia. Caliper measurement of bigonial breadth is also very difficult to perform accurately since both drawn landmarks are not visible simultaneously and the anthropometrist is required to move from side to side while performing the measurement. In general, the AHD derived breadths probably reflect a truer surface breadth since tissue compression was minimal, and the anthropometrist can view each landmark as the probe is placed on it.

## Test Duration

A stopwatch record was kept for each AHD test. Although the time to complete the 28 measurements in a given test varied somewhat for the operators and some reduction in test time was noted across the series, the total test time (from positioning until dismissal) ranged from 3.5 to 6.5 minutes to complete. Approximately 10 minutes were required for completion of the X and Z axis measurements on the NATO headboard, i.e. 17 landmarks x 2 = 34. At least one additional minute would be required to measure the breadths associated with the nine bilateral landmark pairs in order to supply a Y axis value.

# CONCLUSION

The AHD provides true 3-D coordinates and does so at nearly twice the speed at which data from the two axes measured in the traditional NATO headboard can be obtained. In terms of replicability, both intra- and interobserver differences obtained with the AHD are less than those obtained with the traditional technique. Because the operators were able to duplicate coordinate values of other operators nearly as well as they were able to duplicate their own, the reliability of the AHD in the hands of different operators appears to be exceptional.

Empirically, it was determined that the AHD can measure distances at least to 0.1 mm in all three axes. In practice, absolute accuracy depends heavily on the accuracy of calibration values and the diligence of the operators. Test conditions during the validation studies were not ideal. In fact, poor lighting, background noise levels, and limited operational space provided a useful field environment test of the system. After the validation studies were completed, the calibration procedure was updated and made more consistent through use of the calibration fixtures. It was felt that accuracy of the device would continue to improve as operators gained in experience. This will be determined by the analysis of data from the U.S. Army survey of 1987-1988. For the present, it is safe to say that the data collected will, for the first time in any anthropometric survey, provide 3-D landmarks of the head and face in a system useful to designers and engineers.

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## APPENDIX A.

Head and Face Landmarks
Used in the Validation Study

## APPENDIX A.

Head and Face Landmarks
Used in the Validation Study

HEAD/FACE LANDMARK DESCRIPTIONS

Alare, right and left -- the most lateral point on the inferior flare or wing of the nose.

Cheilion, right and left -- the most lateral point of the juncture of the fleshy (mucosal) tissue of the lips with the facial skin at the corner of the mouth.

Crinion -- The lowest point of the hairline on the forehead in the midsagittal plane (on some subjects, the widow's peak).

Ectoorbitale, right and left -- the lateral point of the lateral margin of the orbit at its deepest indentation (near the outer corner of the eye).

Frontotemporale, right and left -- the point of deepest indentation of the temporal crest of the frontal bone above the browridges.

Glabella -- the most anterior point on the frontal bone midway between the bony browridges.

Gonion, right and left -- the most lateral point on the posterior angle of the mandible (jawbone).

Infraorbitale, right and left -- the lowest point on the anterior border of the bony eye socket.

Menton -- the inferior point of the mandible in the midsagittal plane (bottom of the chin).

Promenton -- the most anterior projection of the soft tissue of the chin in the midsagittal line.

Pronasale -- the point of the most anterior projection of the tip of the nose in the midsagittal line.

Sellion -- the point of the deepest depression of the nasal bones at the top of the nose.

Stomion -- the point of intersection of the upper and lower lip on the midsagittal line.

Subnasale -- the point of intersection of the philtrum (groove) of the upper lip and the inferior surface of the nose.

Tragion, right and left -- the superior point on the juncture of the cartilaginous flap (tragus) of the ear with the head.

Zygion, right and left -- the most lateral point on the zygomatic arch.

Zygofrontale, right and left -- the most lateral point of the frontal bone where it forms the upper margin of the bony eye socket.

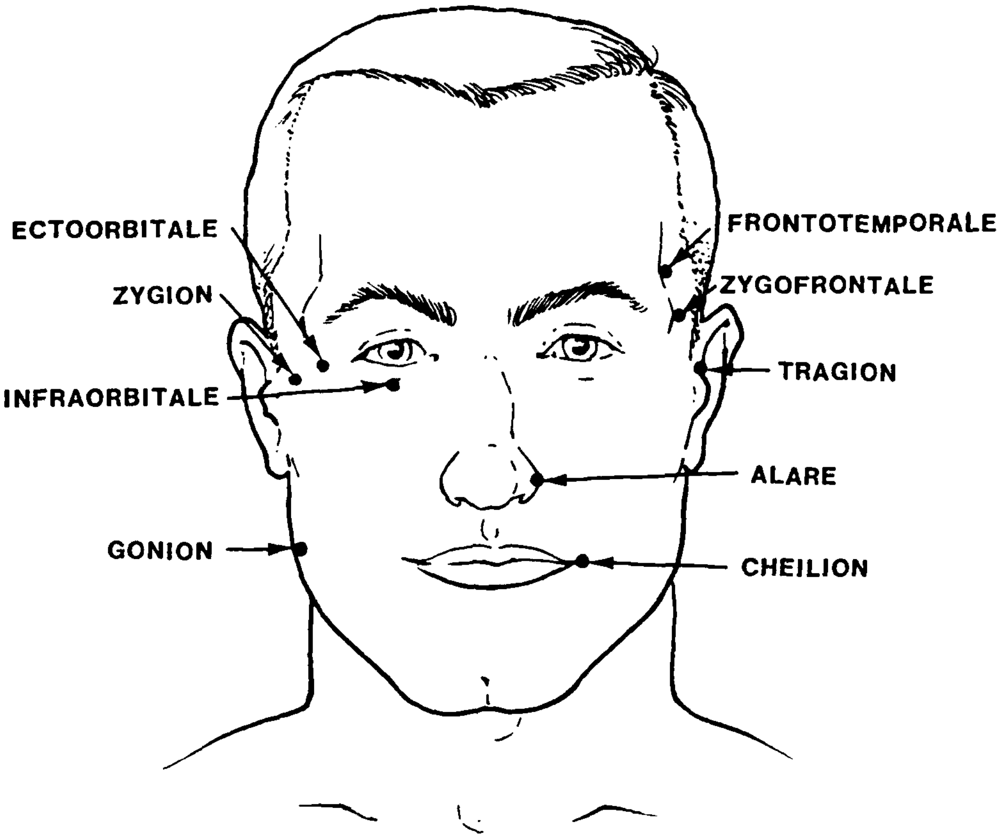



Figure A-1. Location of the bilateral landmarks (shown only on one side).

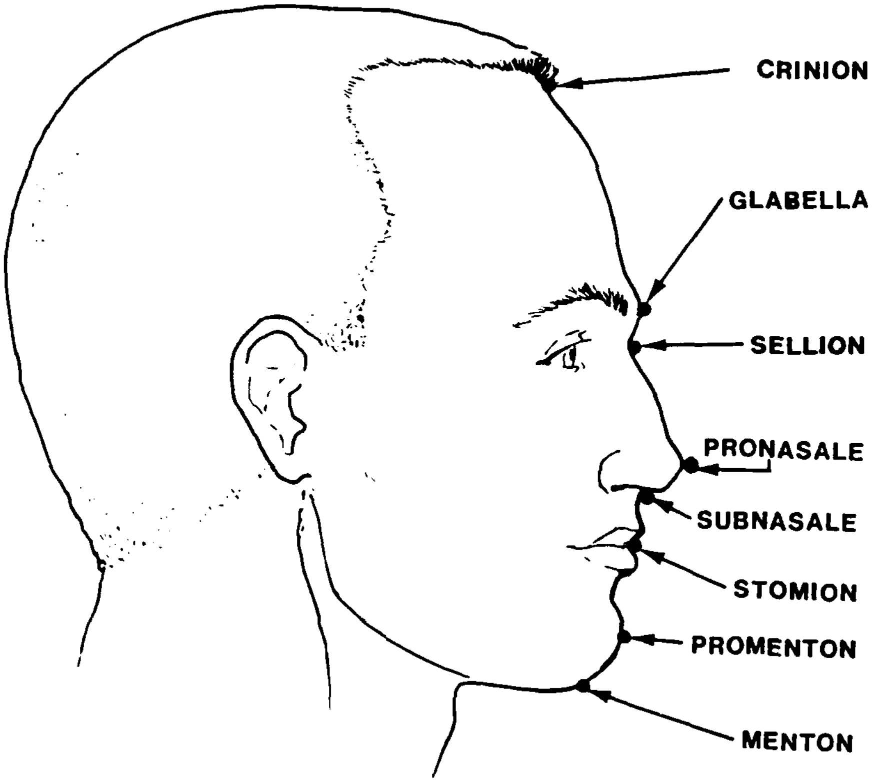



Figure A-2. Location of the midsagittal landmarks.

## APPENDIX B.

Components and Parts List for the AHD

TABLE B-1. Components of the CMS. (See circled numbers on Figures B-1 and B-2.)

| Component Number | Quantity | Description | Part#/Mat'l |
|---|---|---|---|
| 1 | 1 | ENCODER. HEIDENHAIN ROD 450 | PUR. |
| 2 | 4 | S.H.C.S. 1/4-20 x 3 1/4 LG. | ST'D |
| 3 | 3 | S.H.C.S. M 3 x 5 x 16 mm LG. | ST'D |
| 4 | 1 | COUPLING. HELICAL M3015 - 10m - 10m | PUR. |
| 5 | 1 | ENCODER MOUNT | 119-00-02 |
| 6 | 1 | ROTATOR BASE PLATE | 119-00-03 |
| 7 | 1 | BEARING. KAYDON #KF065-XPO | PUR. |
| 8 | 1 | ROTATOR SADDLE PLATE | 119-00-04 |
| 9 | 2 | TORQUE HEAD SCREW. AMERICAN #ADB-53250 | PUR. |
| 10 | 1 | THREADED SPLIT COLLAR. HOLOKROME #15238 | PUR. |
| 11 | 1 | BEARING. ANDREWS #W-1 | PUR. |
| 12 | 1 | ROTATOR SHAFT | 119-00-05 |
| 13 | 1 | VERTICAL SLIDE SUPPORT MOUNT | 119-00-06 |
| 14 | 8 | S.H.C.S. 3/8-16 x 1 LG. | ST'D |
| 15 | 8 | FLAT WASHER 3/8 I.D. | ST'D |
| 16 | 1 | VERTICAL SLIDE BASE | 119-00-07 |
| 17 | 27 | DOWEL PIN 3/16 DIA. x 1" LG. | ST'D |
| 18 | 14 | S.H.C.S. #10-32 x 1 1/4 LG. | ST'D |
| 19 | 2 | SHAFT SUPPORT RAIL. THOMSON #LSR-12 | 119-00-08 |
| 20 | 2 | SHAFT. THOMSON 3/4" DIA. x 20" LG. | 119-00-09 |
| 21 | 4 | BALL PILLOW BLOCKS. THOMSON #RSPB-12-OPN | 119-00-10 |
| 22 | 16 | S.H.C.S. #10-32 x 3/4 LG. | ST'D |
| 23 | 1 | TORQUE HEAD SCREW. AMERICAN #ADB-53255 | PUR. |
| 24 | 1 | VERTICAL SLIDE SADDLE | 119-00-11 |
| 25 | 6 | FLAT WASHER 5/16 I.D. | ST'D |
| 26 | 4 | S.H.C.S. 5/16-18 x 1 3/4 LG. | ST'D |
| 27 | 4 | HEADLINER #HL48-8 | ST'D |
| 28 | 5 | DOWEL PIN 1/2 DIA. x 1 1/4 LG. | ST'D |
| 29 | 1 | HORIZONTAL SLIDE SUPPORT MOUNT | 119-00-12 |
| 30 | 12 | JAM NUT 1/4-20 | ST'D |
| 31 | 16 | SET SCREW. FLAT POINT 1/4-20 x 1" LG. | ST'D |
| 32 | 1 | HORIZONTAL SLIDE BASE | 119-00-13 |
| 33 | 1 | PROBE STYLI. RENISHAW TO SUIT | PUR. |
| 34 | 1 | PROBE. RENISHAW #TP2-5 WAY OR EQUIVALENT | PUR. |
| 35 | 1 | LIGHT SOURCE. MICRO SWITCH FE-TLS3FF | 119-00-18 |
| 36 | 1 | PROBE SOCKET. RENISHAW M8 x 1.25 | PUR. |
| 37 | 1 | SPLIT ROLL PIN 1/8 DIA. x 1 1/2 LG. | ST'D |
| 38 | 8 | S.H.C.S. 1/4-20 x 2 1/2 LG. | ST'D |
| 39 | 2 | SLIDE BEARING ASSEMBLY. TURNOMAT #BUS 1000 | PUR. |
| 40 | 1 | HORIZONTAL SLIDE SHAFT | 119-00-14 |
| 41 | 2 | ALL THREADED ROD 5/8-18 x 1" LG. | ST'D |
| 42 | 3 | PLASTIC BALL KNOB. AMERICAN #ADB-45110 | PUR. |
| 43 | 8 | S.H.C.S. #8-32 x 3/4 LG. | ST'D |
| 44 | 6 | S.H.C.S. #5-40 x 1/2 LG. | ST'D |
| 45 | 1 | RACK. RELIANCE GEAR #R5XG3 | PUR. |
| 46 | 1 | COVER PLATE | 119-00-15 |
| 47 | 2 | PINION. RELIANCE GEAR #P1MS10-20AQ12 | PUR. |
| 48 | 6 | S.H.C.S. MS x 0.8 x 1/2 LG. | ST'D |
| 49 | 1 | FLEX PLATE SUPPORT - HORIZONTAL SLIDE | 119-00-16 |

TABLE B-1. Continued

| Component Number | Quantity | Description | Part#/Mat'l |
|---|---|---|---|
| 50 | 2 | FLEX PLATE. RELIANCE GEAR #FP30 | 119-00-19 |
| 51 | 2 | ENCODER. SPAULDING #532429 | PUR. |
| 52 | 6 | S.H.C.S. #2-56 x 1/4 LG. | ST'D |
| 53 | 2 | REINFORCEMENT BAR | 119-00-17 |
| 54 | 8 | S.H.C.S. #10-32 x 1 LG. | ST'D |
| 55 | 2 | THREADED INSERT. JERGENS #47510 | PUR. |
| 56* | 2 | S.H.C.S. 5/16-18 x 1" LG. | ST'D |
| 57* | 4 | SET SCREW CUP POINT 1/4-20 x 1/4 LG. | ST'D |
| 58 | 1 | FLEX PLATE SUPPORT - VERTICAL SLIDE | 119-00-24 |
| 59 | 1 | ADJUSTABLE STOP MOUNT | 119-00-21 |
| 60 | 2 | SPRING REELS. STOCK DRIVE PROD. #3253-ML-1912 | PUR. |
| 61 | 1 | SPRING REEL MOUNT | 119-00-22 |
| 62 | 1 | JAM NUT #10-32 I.D. | ST'D |
| 63 | 1 | SPINDLE ASS'Y 10-32 | ST'D |
| 64 | 1 | STATIONARY STOP | 119-00-23 |
| 65 | 1 | SAFETY LOCK SCREW | 119-00-25 |
| 66 | 2 | ENCODER ADAPTER | 119-00-74 |

* Not shown.

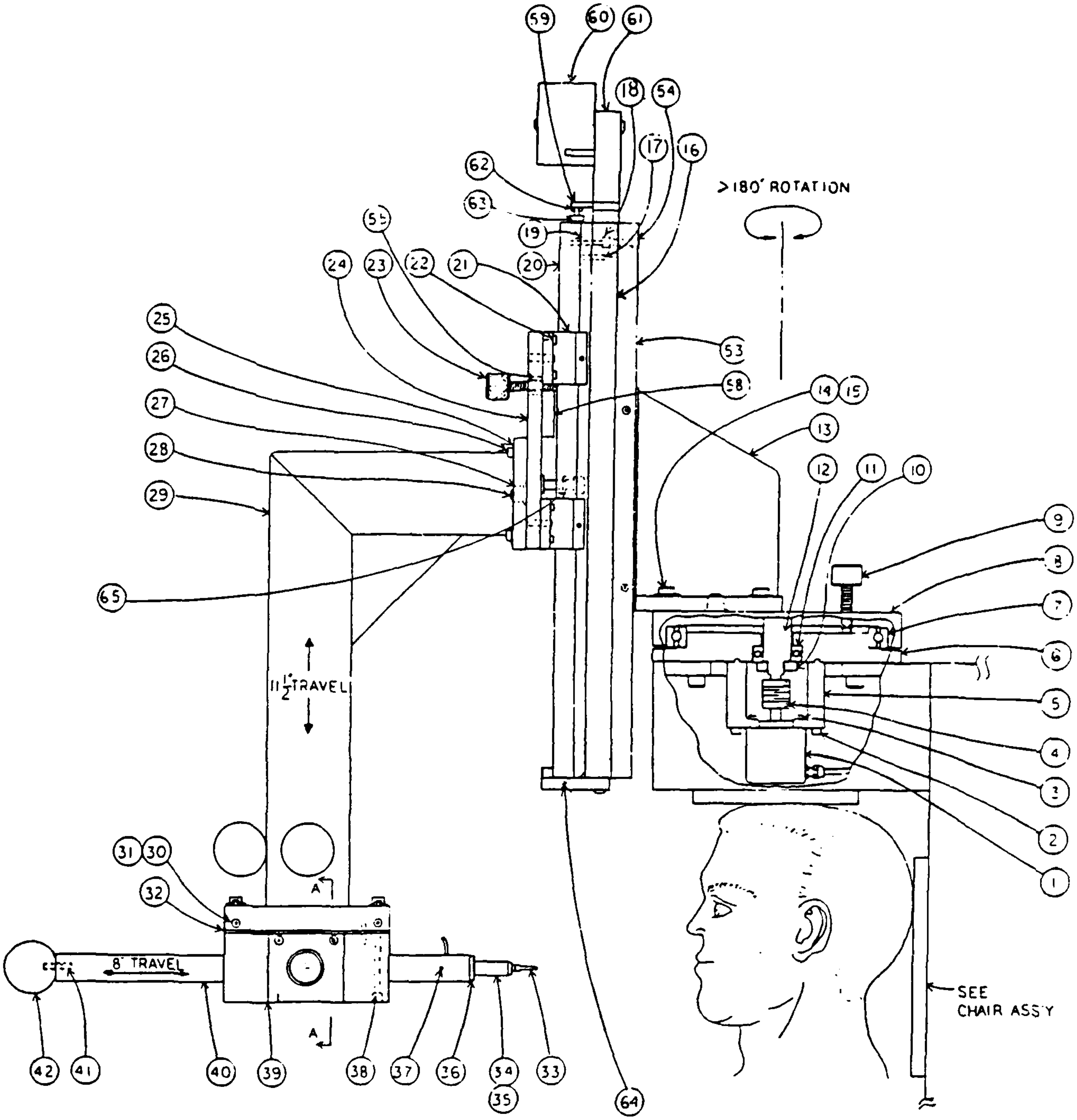



Figure B-1. Mechanical aspects of the coordinate measuring system (CMS). Circled numbers refer to components listed on Table B-1.

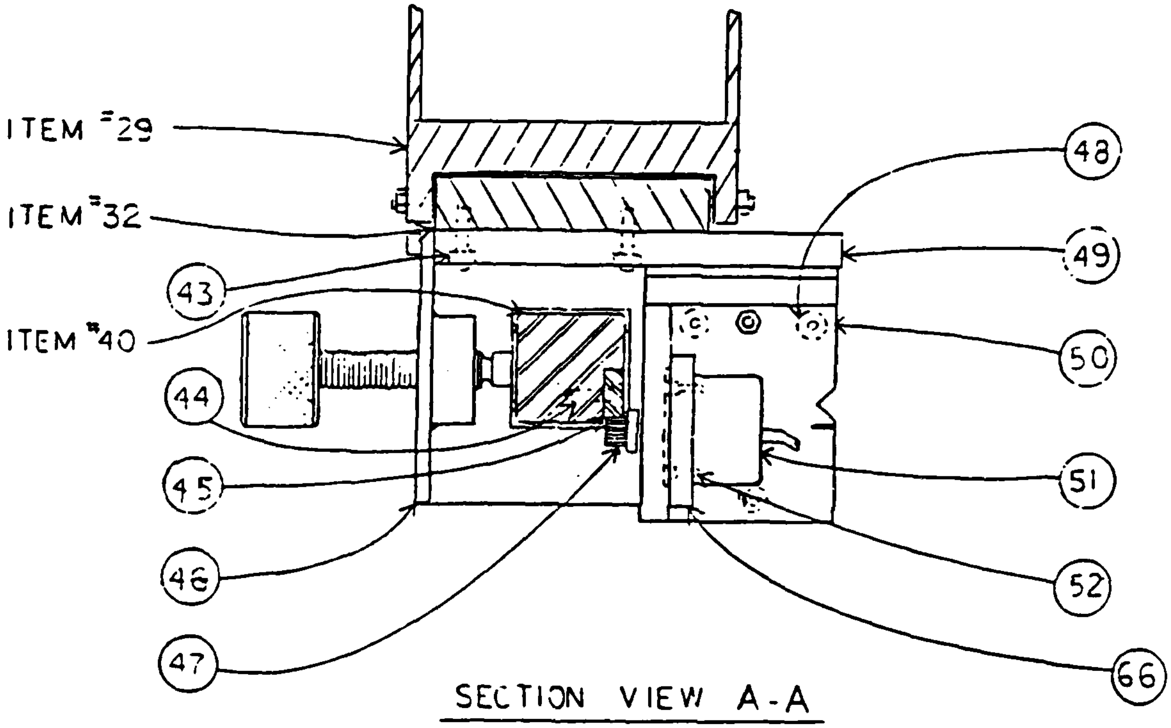



Figure B-2. Cross-sectional detail of the horizontal axis slide assembly located at A on Figure B-1.

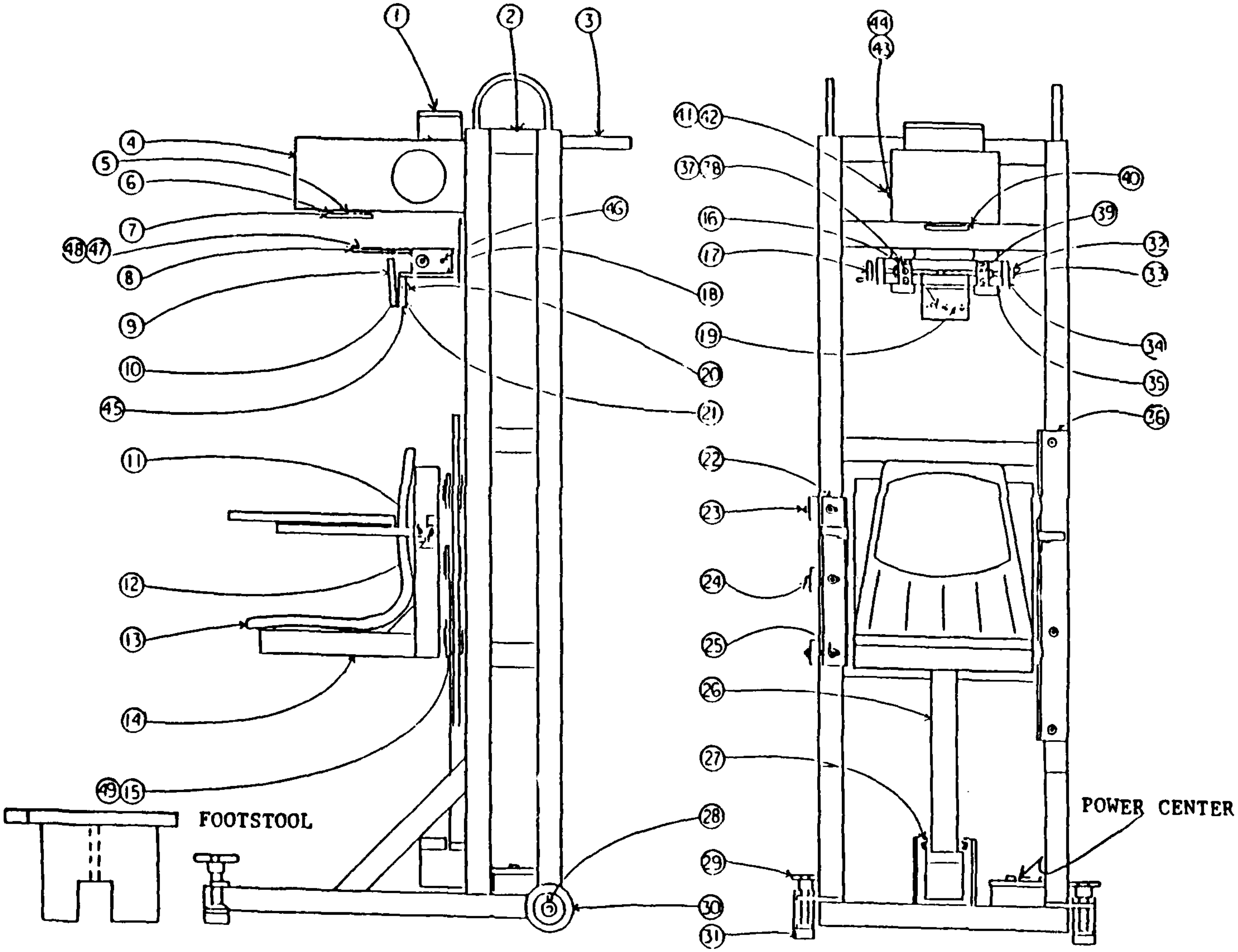



Figure B-3. Mechanical aspects of the support frame and the SPS. (See Table B-2 for description of numbered components.)

TABLE B-2. Components of the Support Frame and the SPS. (See circled numbers on Figure B-3.)

| Component Number | Quantity | Description | Part#/Mat'l |
|---|---|---|---|
| 1 | 1 | COUNTER. HEIDENHAIN #EXE-610 | PUR. |
| 2 | 1 | FRAME | 119-00-32 |
| 3 | 2 | HAND GRIPS | TO SUIT |
| 4 | 1 | HEADBOARD SUPPORT HOUSING | 119-00-31 |
| 5 | 1 | SUBMINI SPST MOMENTARY MOUNT | 119-00-73 |
| 6 | 2 | SHOULDER BOLT 1/4 x 1" LG. | ST'D |
| 7 | 1 | UPPER HEADBOARD PIECE 0.5" THICK LUCITE™ | 119-00-35 |
| 8 | 1 | HEAD STABILIZATION CLAMP | 119-00-66 |
| 9 | 1 | REAR HEADBOARD PIECE 0.5" THICK LUCITE™ | 119-00-67 |
| 10 | 1 | SPRING | TO SUIT |
| 11 | 2 | BALL PLUNGER 3/8-16 x 3/4" LG. | ST'D |
| 12 | 2 | SHOULDER BOLT 3/8 x 3/4" LG. | ST'D |
| 13 | 1 | CHAIR. AMIGO #270250 | PUR. |
| 14 | 1 | SEAT FRAME | 119-00-30 |
| 15 | 3 | V-TRAC WHEELS. RAPISTAN #VNRX 1 1/2 x 4 5/8 | PUR. |
| 16 | 2 | SUBMINIATURE PUSH BUTTON SWITCH. ARCHER 275-1571 | PUR. |
| 17 | 1 | HANDWHEEL. AMERICAN #ADB-47164 | PUR. |
| 18 | 1 | REAR HEADBOARD MOUNT SUPPORT | 119-00-68 |
| 19 | 1 | SET SCREW 3/8-16 x 3/4" LG. | ST'D |
| 20 | 2 | SHOULDER BOLT 1/4 x 3/4 LG. | ST'D |
| 21 | 1 | REAR HEADBOARD MOUNT | 119-00-69 |
| 22 | 1 | SHORT RAIL | 119-00-34 |
| 23 | 3 | SET SCREW 3/8-16 x 1" LG. | ST'D |
| 24 | 4 | JAM NUT 3/8-16 | ST'D |
| 25 | 13 | S.H.C.S. 3/8-16 x 1" LG. | ST'D |
| 26 | 1 | LINEAR ACTUATOR. SAGINAW STEERING GEAR #500733 | PUR. |
| 27 | 2 | ROLL PIN. 1/8 x 1" LG. | ST'D |
| 28 | 2 | SHOULDER BOLT 1/2 x 2" LG. | ST'D |
| 29 | 2 | HAND KNOB & SCREW. AMERICAN #ADB-30235 | PUR. |
| 30 | 2 | TREAD WHEELS. RAPISTAN #4 x 1 1/2-AD1RX-1/2 | PUR. |
| 31 | 2 | LEVELING PADS | 119-00-70 |
| 32 | 2 | ONE PIECE SPLIT SHAFT COLLAR 1/2 I.D. | ST'D |
| 33 | 1 | RIGHT & LEFT HAND THREADED SCREW | 119-00-71 |
| 34 | 2 | END PLATE | 119-00-62 |
| 35 | 1 | BASE PLATE | 119-00-61 |
| 36 | 1 | LONG RAIL | 119-00-33 |
| 37 | 2 | SADDLE PLATE | 119-00-64 |
| 38 | 1 | HEAD STABILIZATION CLAMP | 119-00-65 |
| 39 | 4 | FLAT HEAD 1/4-20 x 3/4 LG. | ST'D |
| 40 | 1 | SUBMINI LEVER SWITCH. ARCHER #275-016 | PUR. |

TABLE B-2. Continued.

| Component Number | Quantity | Description | Part#/Mat'l |
|---|---|---|---|
| 41 | 1 | SUBMINI ROLLER LEVER SWITCH. ARCHER #275-017 | PUR. |
| 42 | 4 | #3-56 BOLT x 1/2 LG. | ST'D |
| 43 | 1 | SUBMINI ROLLER LEVER SWITCH MOUNT | 119-00-72 |
| 44 | 2 | SET SCREW 10-32 x 1/2 LG. | ST'D |
| 45 | 8 | BUTTON HEAD 10-32 x 3/4 LG. | ST'D |
| 46 | 6 | BUTTON HEAD 1/4-20 x 1" LG. | ST'D |
| 47 | 2 | NEOPRENE SPONGE TUBING 3/8 I.D. x 1 1/8 O.D. | TO SUIT |
| 48 | 2 | HOSE 1/4 I.D. | TO SUIT |
| 49 | 3 | SHOULDER BOLT 5/8 DIA. x 2" LG. | ST'D |

**APPENDIX C.**

Electrical Aspects of the AHD Subsystems

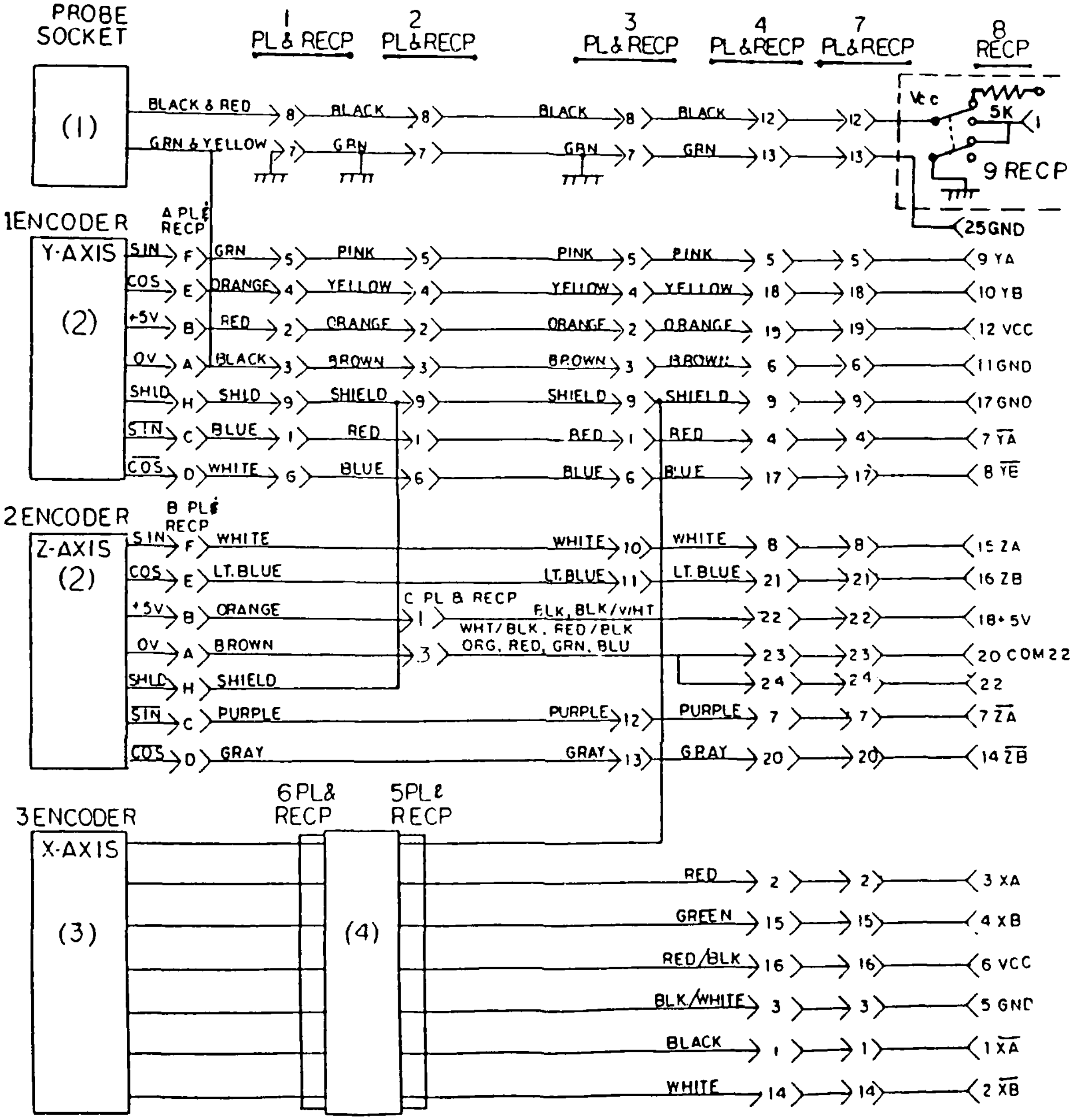



Figure C-1. Electrical wiring diagram for the coordinate measuring system (CMS), revised.

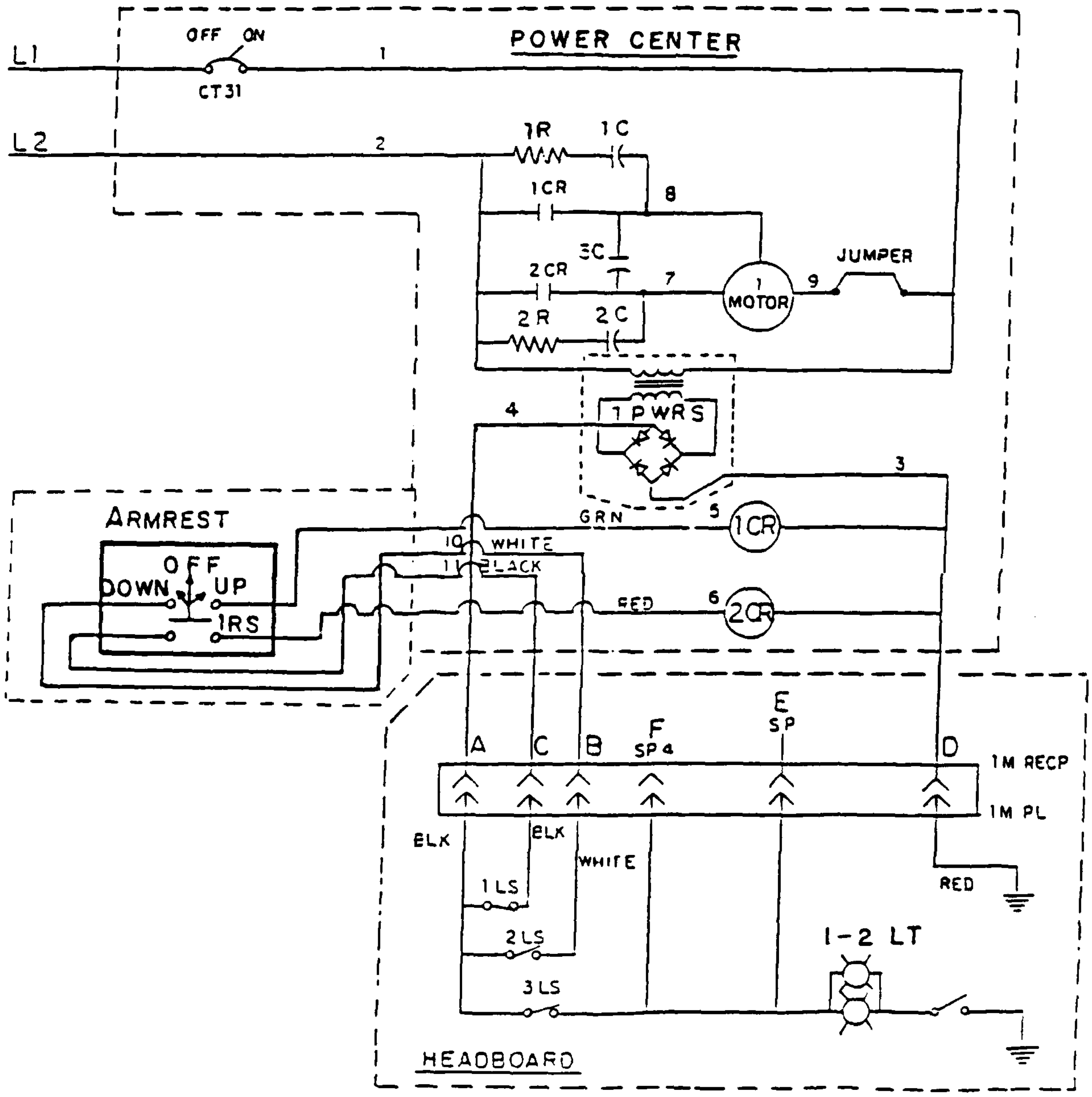



Figure C-2. Wiring diagram for the subject positioning system (SPS), including items in the power box, revised.

TABLE C-1. Electrical Components of the SPS Including Items in the Power Center Box.*

| I.D. | Quan. | Description | Part # | Supplier |
|---|---|---|---|---|
| 1 PWRS | 1 | POWER SUPPLY | #273-1653 | TANDY |
| CT31 | 1 | CIRCUIT BREAKER | #W31X2A 16-5 | POTTER-BRUMFIELD |
| 1 & 2 CR | 2 | RELAYS, 12VDC | #275-226 | TANDY |
| 1,2 & 3 C | 3 | CAPACITORS, 47 MFD, 400WVDC | | TANDY |
| 1 RS | 1 | ROCKER SWITCH | #MR1-121 | CUTLER-HAMMER |
| 1 & 2 LT | 2 | PILOT LIGHTS, RED | | |
| 3 LS | 1 | LIMIT SWITCH | #275-1571 | TANDY |
| 1 & 2 LS | 2 | LIMIT SWITCH | #275-017 | TANDY |
| 1 & 2 R | 2 | RESISTORS, 200 OHM, 0.5W | | TANDY |

* See Figure C-2 for location of ID labelled components.

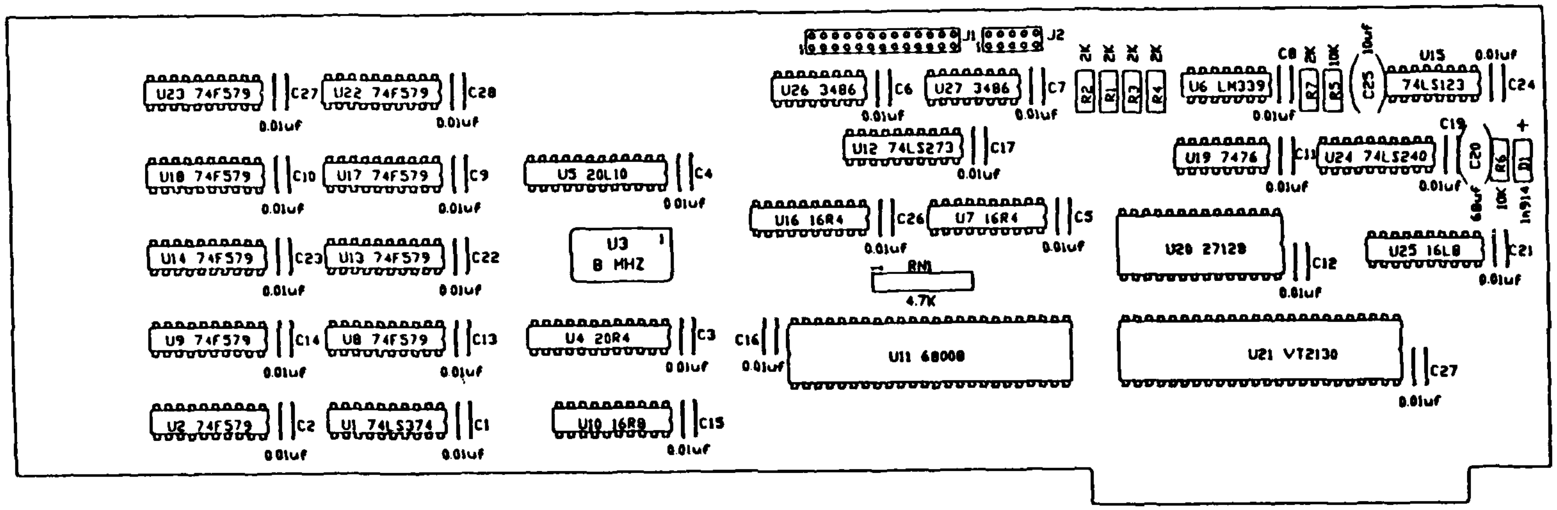



Figure C-3. Component layout of the printed circuit board for the CMS.

## APPENDIX D.

Instruction Manual for the Operation and Maintenance
of the Automated Headboard Device

APPENDIX D.

Instruction Manual for the Operation and Maintenance
of the Automated Headboard Device

## GENERAL DESCRIPTION

The automated headboard device (AHD) was specifically designed and constructed for the measurement of three-dimensional (3-D) coordinates of the head and face. The coordinates are defined in terms of three mutually perpendicular axes (X, Y, and Z) referenced to the intersection of two plane surfaces (headboards) against which a subject's head is positioned for measurement as shown in Figure D-1.

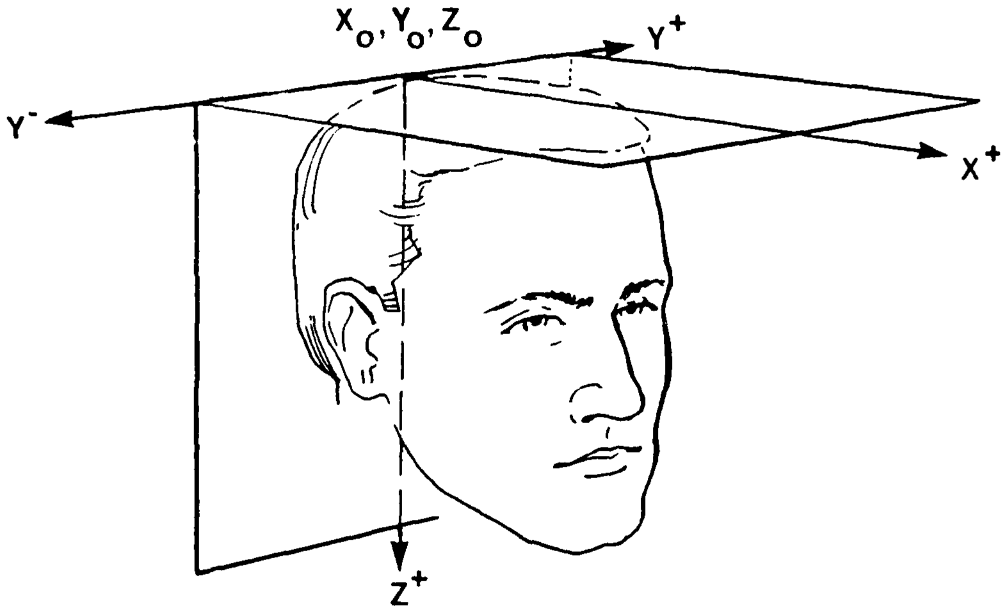



Figure D-1. Axis system for headboard measurements.

The principal components of the AHD are shown in Figure D-2. Basically, the device consists of the tubular steel frame which supports the subject positioning system (SPS), the coordinate measuring system (CMS), and the associated subassemblies necessary for control operations. The support frame is equipped with wheels, and is designed as a transport "dolly" to facilitate movement from site to site in field operations. The molded plastic seat pan is equipped with an electrically powered lift system which raises and lowers a seated subject through a range of 30 cm (12 inches). This range of adjustability permits the AHD to accommodate persons with sitting heights from 74 cm (29 inches) to approximately 104 cm (41 inches).

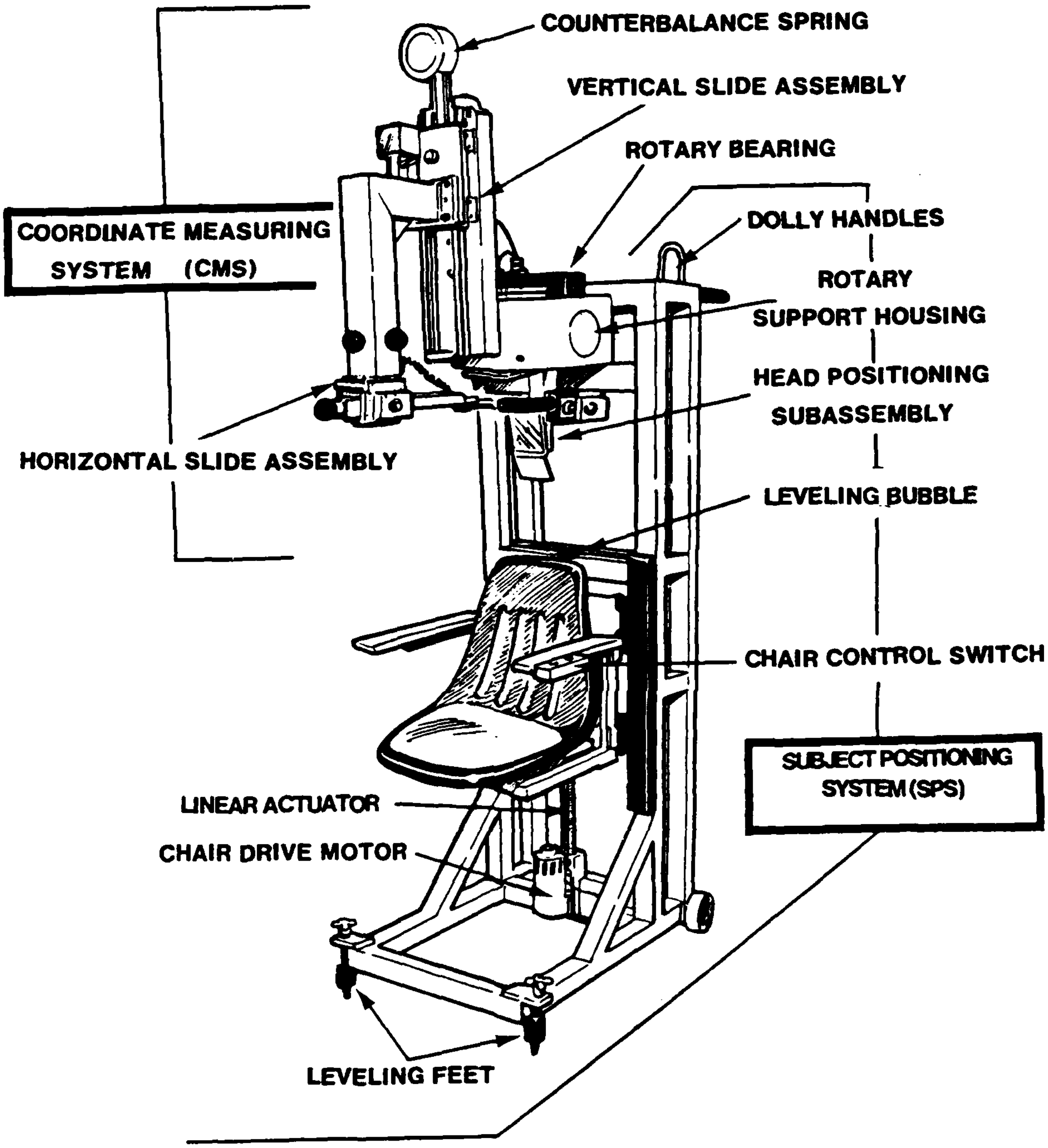



Figure D-2. Principal components of the automated headboard device.

The instrumentation and hardware which comprise the CMS, exclusive of the computer, are suspended from the top aspect of the support frame. Also, immediately under the rounded structure near the top of the AHD (rotary support housing) are the two reference planes (the top and rear headboard pieces) and the adjustable head stabilization clamp, which along with the chair constitute the major components of the SPS. Some of the details of this equipment are illustrated in Figure D-3.

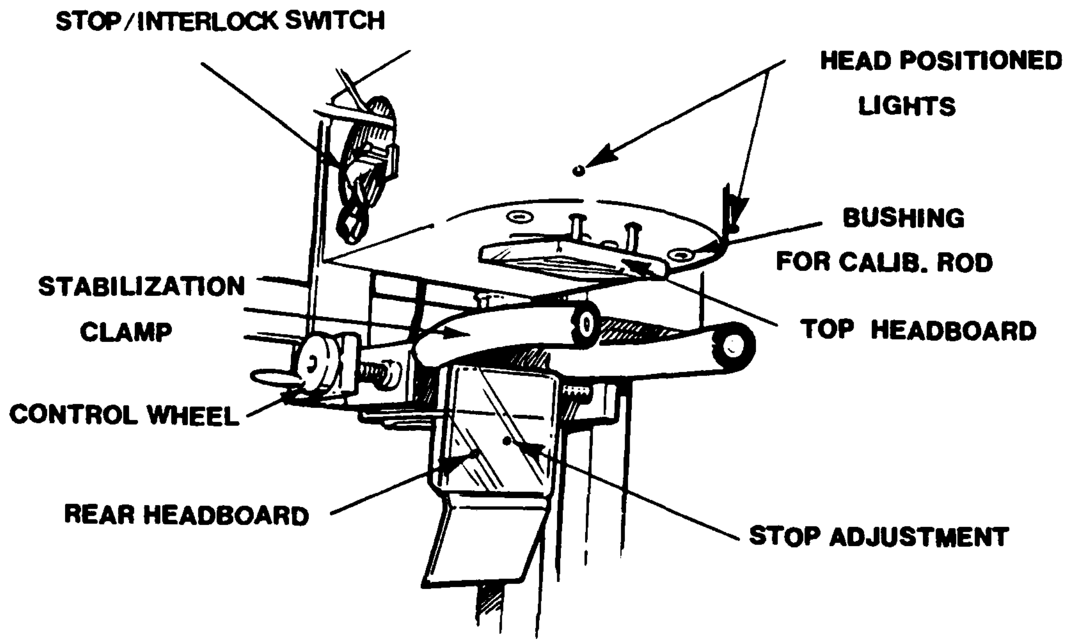



Figure D-3. The reference planes (headboards) and head stabilization clamp.

Mechanically, the CMS consists of a moveable arm, which may be rotated through approximately 200° (rotary bearing), moved in or out 220 mm (horizontal slide), or moved up and down nearly 300 mm (vertical slide). These are shown in Figure D-4. In operation, the objective is to bring a small ruby bead (2-mm diameter) located on the touch probe at the inner end of the horizontal slide into light contact with a given point for which coordinates are to be determined. The CMS is calibrated so that the location of the center of the bead relative to the headboard surfaces is known to the nearest 0.1 mm in each axis. Coordinates of a point may be recorded automatically by a slight pressure on the bead stylus (AUTO TRIP mode)* or points may be recorded manually (MANUAL TRIP mode) as the bead contacts the surface of the measured object. Since the AHD was designed to be principally

* The CMS, with the exception of the probe, is wired so that the AUTO TRIP mode is an option. The device does not currently use an AUTO TRIP probe. If future users wish to modify the current probe or attach a new probe, the AUTO TRIP mode will be fully functional.

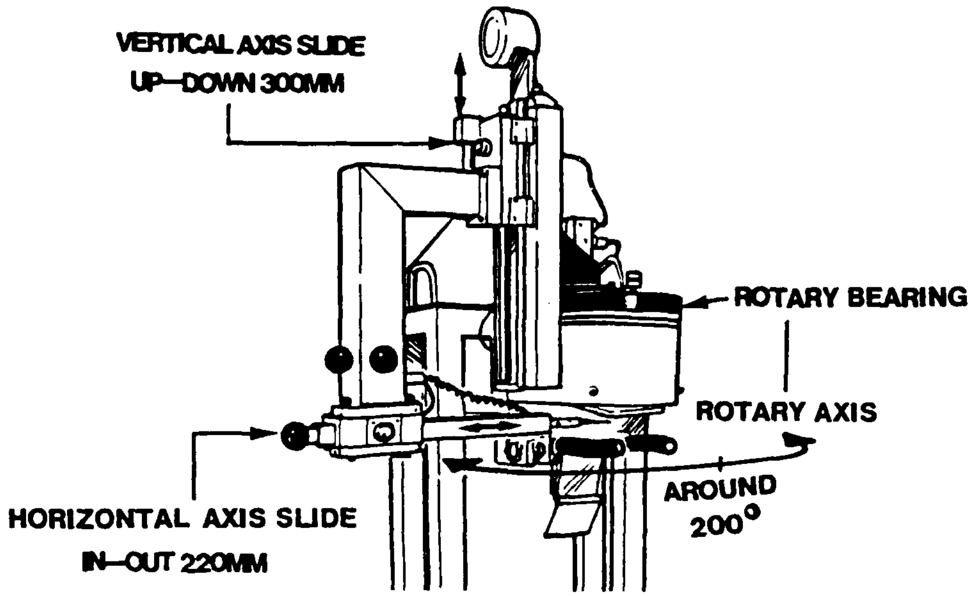



Figure D-4. The axis assemblies of the coordinate measuring system (CMS) and their range of movement.

used with live test subjects, and because the pressure needed to "auto-trip" the touch probe was found to result in an undesirable amount of deformation of soft tissue, the MANUAL TRIP mode is normally used. A remote switch box is provided which may be used to manually "trip" the probe at any time with minimal deformation of the skin.

As the probe is moved around the face to selected points (landmarks), electrical devices called encoders, attached to each of the movable parts of the CMS, act to convert the movements into electrical pulses that are equivalent to distance. In order to convert these analog (A) signals into digital (D) coordinate values for the three axes, the CMS is designed to operate with a personal computer (PC) which has been programmed to perform the A - D conversions, total the pulse counts, and perform the necessary trigonometric calculations. So that the values computed accurately reflect distance along each axis from their common origin (see Figure D-1), the CMS must be calibrated periodically using a fixture of precisely known dimensions.

## OPERATION OF THE AHD

In the sections of the manual presented below, the recommended procedures to be used in operating the AHD are outlined sequentially, beginning with instructions for unloading and setting up the AHD which will take two people. Although the AHD was constructed to be as rugged as possible and is basically a field device, it contains very sensitive and delicate instrumentation. For this reason, one section of the manual deals with the care and maintenance of the AHD.

## Setting Up

1. Make sure the site selected for setting up this device has a firm, smooth, and relatively level surface. Approximately 100 square feet of work area will be required. Convenient access to 110 volts AC to power the AHD and its accompanying computer should be nearby, since the power cords are typically less than 10 feet in length. The connecting cable between the AHD and the computer is approximately 15 feet in length.

2. When the AHD is at the station location, remove any loose items transported on the support frame dolly. Place the support frame in the vertical upright position as shown in Figure D-2. Level the frame by adjusting the leveling feet appropriately. The leveling feet are located at the front of the support frame base (see Figure D-2). A leveling bubble is located on the cross brace just behind the top of the chair. Before proceeding to the next step, make sure the frame is stable.

3. Unlatch and remove the vertical axis assembly from its fiber glass shipping container as shown in Figure D-5. Position the assembly on the two alignment pins found on top of the rotary bearing housing. The housing as it will appear without the assembly in place is shown in the photograph in Figure D-6. The appearance of the assembly by itself is shown in Figure D-7. Since the assembly weighs approximately 10 kg (22 pounds), assistance may be required to lift it into position. When securely in place, insert and tighten the four retainer bolts with a 5/16" Allen wrench provided in the tool kit for the AHD. The locations of the retainer bolts are shown in Figure D-8. Next, attach and secure the computer cable connector as shown in Figure D-8.

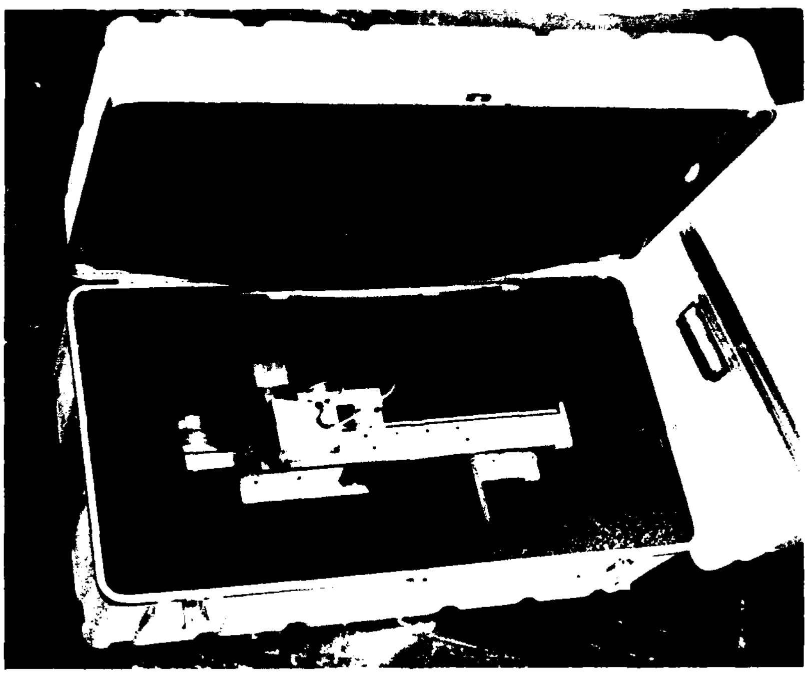


Figure D-5. The vertical slide assembly shown partially unpacked in its shipping container.

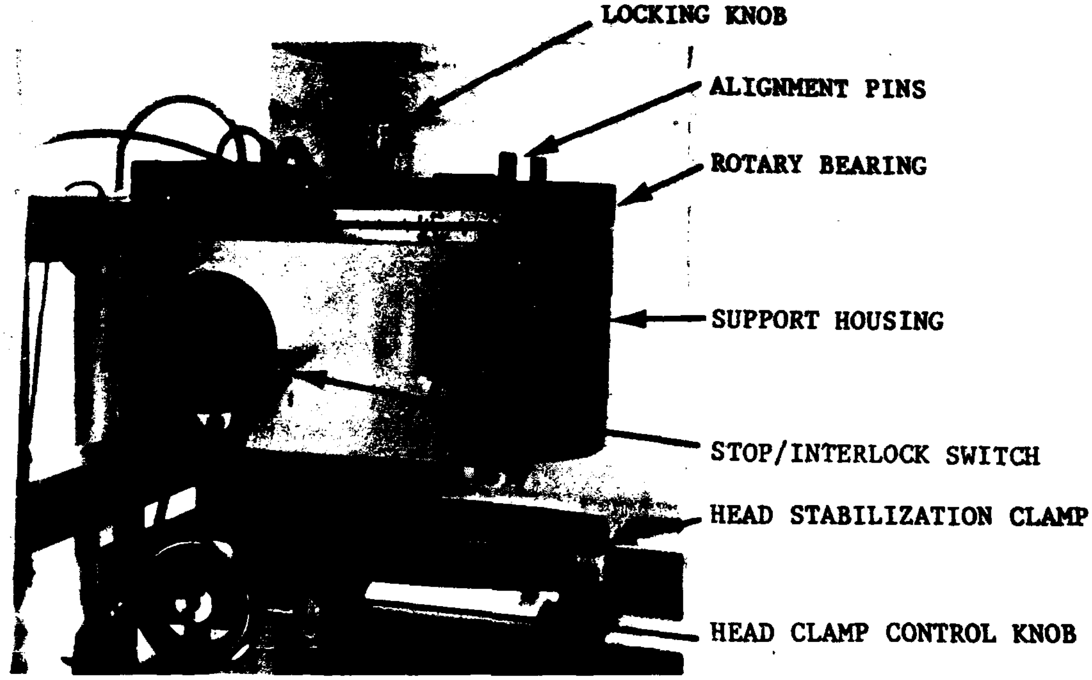



Figure D-6. The rotary bearing and the support housing with the vertical axis assembly removed.

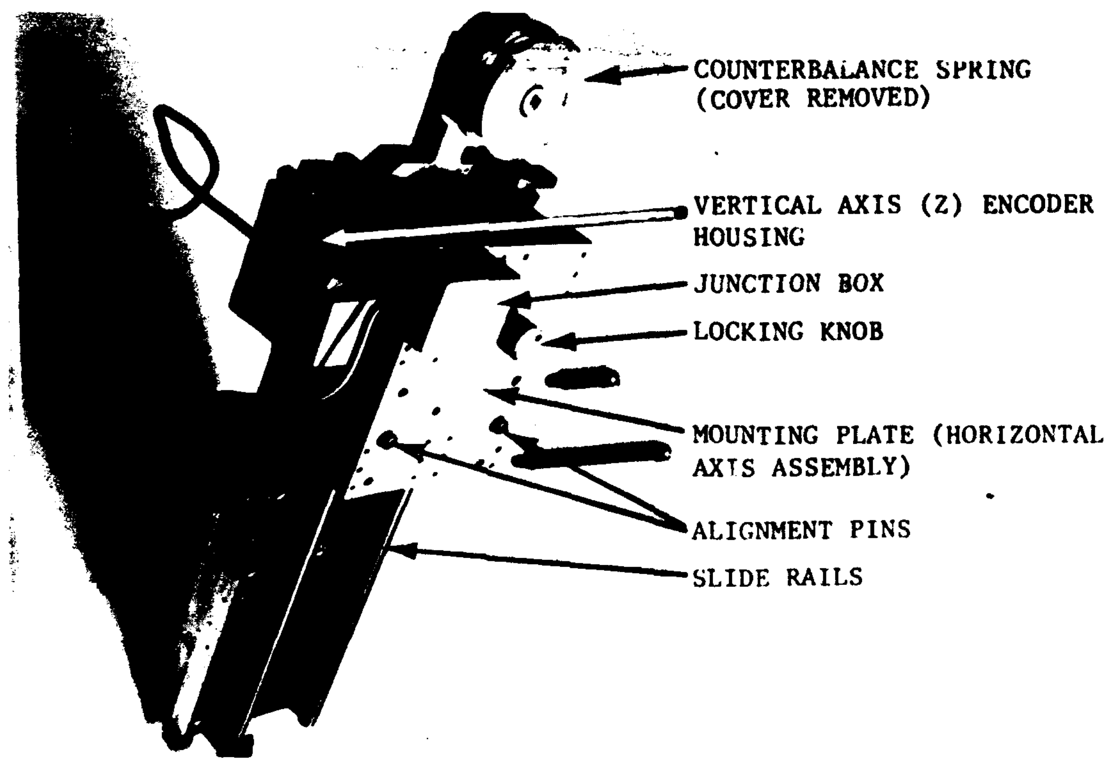



Figure D-7. The vertical axis assembly.

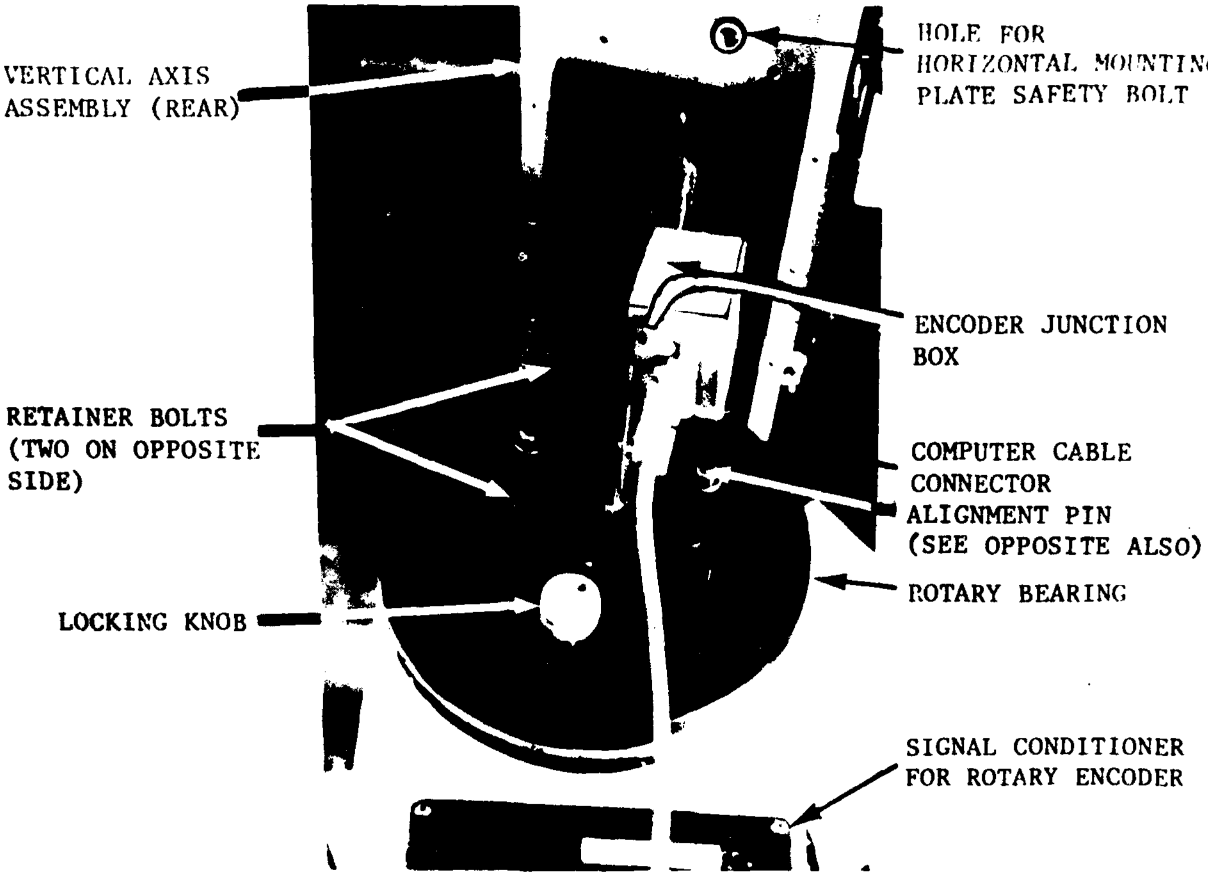



Figure D-8. The rotary bearing and the back of the vertical axis assembly viewed from above and behind.

4. Unlatch and remove the horizontal slide assembly from its shipping container shown in Figure D-9. The appearance of the assembly arm when it is disassembled is shown in Figure D-10. Mount the assembly on the alignment pins near the bottom of the vertical axis assembly which was just installed. The location of the alignment pins is indicated in Figure D-7. Have an assistant hold the assembly in place while you insert and tighten the four retainer bolts with a 1/4" Allen wrench. Insert and secure the encoder cable connector on the junction box located on the lower left of the vertical axis assembly.

Figure D-9. The horizontal axis slide assembly and arm in its shipping container.

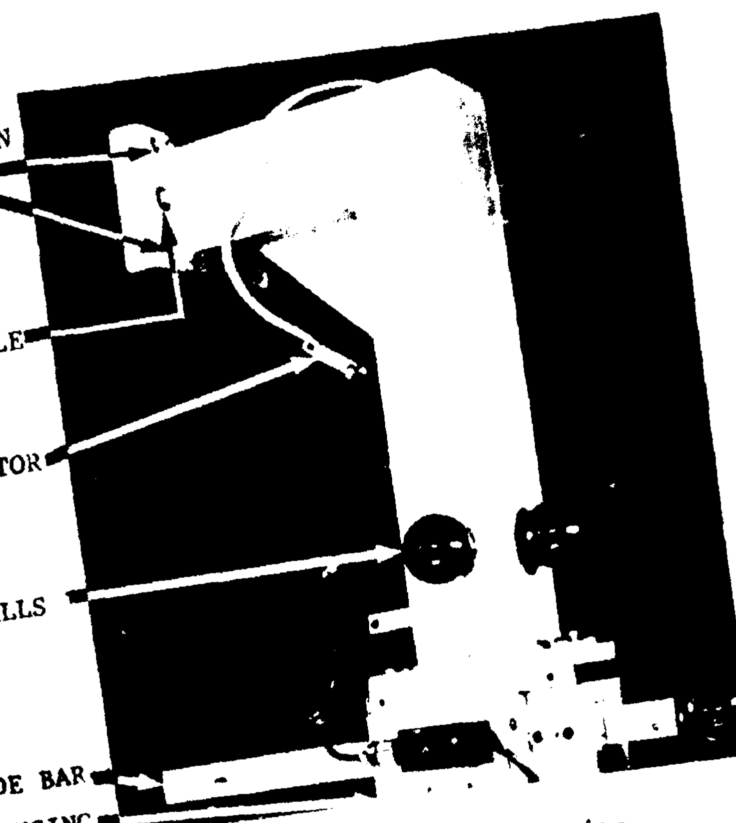



Figure D-10. The horizontal axis slide assembly and its mounting arm.

5. Locate the hole for the safety bolt on the rear of the vertical axis assembly structure. The hole is marked (see Figure D-8). The double action set screw is backed out of the mounting plate for the horizontal axis assembly, and screwed into the body of the vertical axis assembly by turning the screw clockwise (CW) with a 1/4" Allen wrench. This screw prevents the horizontal axis mounting plate from moving during shipment or setup due to "pull" from the counterbalance spring. (NOTE: The safety bolt is restored into the mounting plate during disassembly).

6. Loosen the locking knobs on all three axes. The rotary and vertical locking knobs are shown in Figure D-6 and Figure D-7, respectively. The horizontal axis locking knob can be seen (though it is not labeled) on the horizontal axis slide housing in Figure D-4. In order to loosen the locking knobs, turn approximately one quarter turn, counterclockwise (CCW). Test each axis for free and easy movement and then lightly apply a few drops of machine oil to the vertical slide bar and the horizontal slide rails. Wipe both surfaces clean with a soft, lint-free cloth. Position the arm in the full left (as you face the AHD) position against the stop/interlock switch (Figure D-6) and then tighten the rotary locking knob. Fully withdraw the horizontal slide and tighten its locking knob. Move the vertical assembly tightly against its upper stop and, while holding it in place, tighten the locking knob. This positioning of the slide assemblies is called the BEGIN-END condition.

7. Recheck all encoder connectors to make sure they are all secure. Plug in and secure the main connector for the computer cable (see Figure D-8). At this time the remote (or manual) touch probe switch may also be plugged in to a small jack located on the peripheral connectors panel of the computer.

8. Plug the power cord for the AHD into the power strip provided. Plug the power strip, or if necessary an extension cord, into the nearest grounded (three-prong) 110-volt AC outlet. If a grounded outlet is not available, connect the AHD and the computer, using the grounding strap supplied with the tool/supply kit, to the nearest available good grounding source, e.g., conduit, water pipe or radiator. Be sure the system is plugged through the ground fault interruptor supplied at some point in the power line.

9. Turn on the power with the switch located on top of the power box found on the bottom cross brace of the support frame in the rear of the AHD.

10. Check the "Head Positioned" indicator lights by simultaneously depressing both the headboards against their stops. The red indicator lights located on the rotary support housing (see Figure D-3) should light. If the lights do not come on, adjust the stop set screws with a 1/8" Allen wrench slightly, either CW for increasing the "stop" position, or CCW for lessening the stop position and increasing the angle between the headboards. The lights are activated when the planes are in position against their stops. The switches are incorporated in the stops. Periodically, check the planes to ensure that a right angle is obtained just as the lights are turned on.

11. Check the chair lift for proper action by depressing the UP-DOWN switch button located in the chair arm rest to the operator's right. As a safety factor, the chair <u>cannot</u> be lowered unless the CMS arm is against

the stop/interlock switch located on the left side of the housing (see Figure D-6). If the chair lift still does not work, check that the AHD has power and that the breaker in the power center box has not been tripped.

12. Remove the touch probe from its storage box and screw it into the end of the horizontal axis slide bar (see Figure D-11). The probe is extremely delicate and expensive so great care should be taken when handling it.

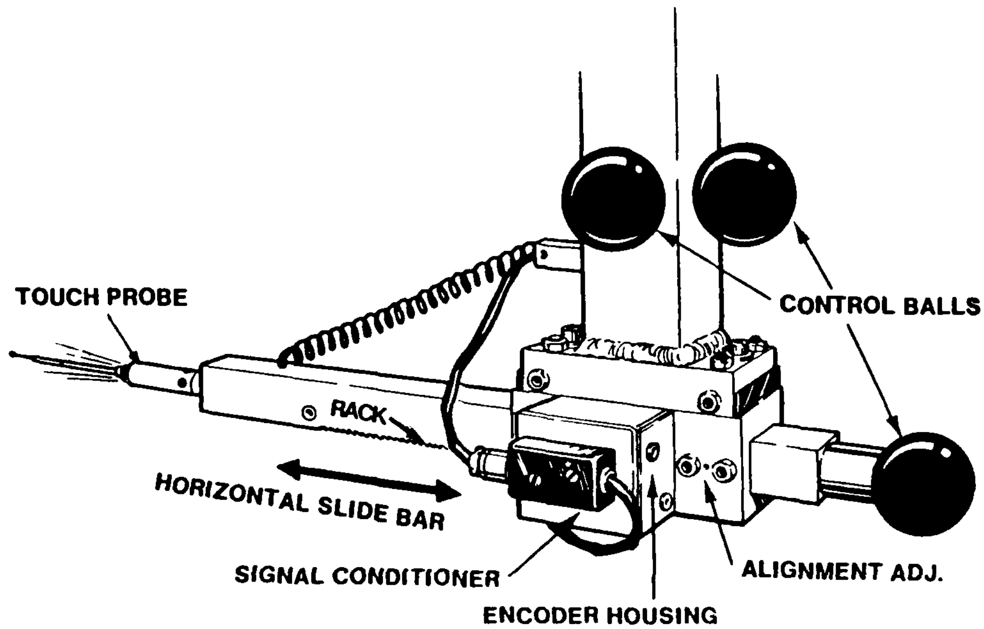



Figure D-11. Horizontal slide assembly showing the touch probe and the measurement instrumentation.

13. You are now ready to set up the computer in preparation for calibrating the CMS.

## Loading the Program

The coordinate measuring system (CMS) is designed to operate in conjunction with a COMPAQ II portable computer in which there has already been installed a printed circuit board containing the necessary components for processing the pulses coming from the encoders. For the location of the expansion slots refer to the Operator's Guide for the computer. Additional software needed for the computation and display of the coordinates, calibration of the system, listing of the landmarks to be sampled, storage and printout of the data collected, and other functions is contained on a 5 1/4" double density disk. In booting the system for the measurement of coordinates, the diskette should be loaded into the computer.

Before turning on the computer and the printer, make sure the CMS and printer cables are plugged into the appropriate connectors located on the peripherals panel of the computer. The arm of the CMS must be positioned

tight against the stop/interlock switch with the horizontal slide fully retracted and the vertical slide against the upper stop. This is the BEGIN-END position. The CMS must be in this position each time the computer is turned on, since a position value for the rotary encoder is placed in the software at that time. If you should fail to start with the arm in the BEGIN-END position, calibration values will be wrong. Turn off the computer, position the arm correctly, and restart the program. If not already installed, the hand (trip) switch box should be plugged into the end of the CMS board at this time. If an assistant is to use the switch to enter coordinates for each point into the computer, place the small toggle switch at the expansion slot in the DOWN position. As noted previously, with the switch in the UP position a properly equipped touch probe may also be "auto-tripped". The remote hand switch is shown in Figure D-12.

Figure D-12. Remote hand switch for manual recording of coordinates.

Insert the CMS program disk into DRIVE A and power up the computer and printer. The Disk Operating System* (DOS) displays a date -- usually the current one -- and asks for a new date. If the date on the screen is correct, press the key marked "enter;" otherwise, type the correct date, and then press "enter." Next, DOS displays a time. If the time is correct, press "enter;" if it is not, type the correct time, and then press "enter."

When the date and time are entered, a prompt will be displayed on the left side of the screen: A>.

At this point, before the AHD program is loaded, the directory of the station disk should be checked. This need not always be done, but when you use a new station disk for the first time it is best to verify that several

* Compaq Personal Computer MS-DOS, Version 3.20
Copyright Compaq Computer Corp. 1982, 1986
Copyright Microsoft Corp. 1981, 1986

files are on the disk. To do this, type "DIR" after the prompt, and press "enter." DOS will respond with a list of the files on the disk in drive A:

**COMMAND.COM**

**START.COM**

**POINTS.TXT**

**REG**

These may appear in any order. If the disk has been used before, a file named **GAGE.PRM** will also be present. **GAGE.PRM** is created by the calibration procedure within the AHD program, and it is deleted and recreated each time the machine is calibrated. If only **GAGE.PRM** is missing, you may load the AHD program as described below; if any of the other four files are missing, you should replace the disk with one which contains all four before loading the program.

To start the AHD program, type "start" at the DOS prompt and press "enter". The program takes a few seconds to load. Once loaded, it automatically begins with the calibration procedure, which is described in detail below (see CALIBRATING THE CMS). After calibration has been completed, the monitor will display the menu options and the XYZ values ($\pm$ 2 mm) shown below:

| | |
|---|---|
| **X** | **60** |
| **Y** | **-216** |
| **Z** | **13** |

1. **calibrate**
2. **record points**
3. **retest a subject**
4. **print a file**
5. **display Subject.Num file**
6. **display machine coordinates**
7. **terminate program**

This display is the main menu, from which any of seven operations can be chosen. To select an operation, press the corresponding number on the keyboard. The purpose and function of each operation is described on the following pages.

Three of the operations listed on the menu -- **record points, retest a subject**, and **print a file** -- use the subject number to generate data file names or to locate existing data files. You will be asked to enter the subject number one time for each subject; most often this will occur when you select **record points**, because that is usually the first of the three procedures to be run on a subject.

Each time they are called, these procedures read the subject number from the "Subject.Num" file on the subject's disk. The program also retains in memory the subject number it read from the disk for the previous subject. Whenever the new subject number does not match the number in the memory, the program asks you to verify the new number by typing it in.

The program is designed to flag such errors as mis-entering a subject's number or recording data on the wrong disk. It provides a number of error messages and "second chances" to enable the operator to make the indicated corrections.

The seven menu items are individually described below:

1. **Calibrate**: As noted, the CMS must be calibrated before the seven-point menu appears. However, **calibrate** may be selected at any point later in the procedure if the X, Y, or Z values displayed above the menu items fall outside the ± 2 mm range, indicating the need for recalibration.

The procedure begins with the display: **Set axes to fixture? (y/n).** If you press "N", "n", or "-" (the minus sign), the program will return to the main menu. If you press "Y", "y", or "+", the program will ask you to input certain coordinates as described in the next section, CALIBRATING THE CMS. After the calibration is complete, the program returns to the main menu.

2. **Record points**: Following the calibration procedure and for each subject who is measured, this menu item prepares the system to receive and record a specific list of head-face landmark coordinates in a specific order. The program prompts the measurer by displaying the name and number of each landmark on the screen. As each successive landmark is measured, the name of the next landmark will appear. When the measurement of a given subject is complete, the program "edits" the data by checking to make sure that the relative positions of the measured points with respect to each other are reasonable. If they are not, subjects are remeasured. The coordinate values for each landmark are recorded and stored on the subject diskette in Drive B.

3. **Retest a subject**: This item is included so that the operator may choose to remeasure a subject. Using a different data file name (automatically generated in the computer), it receives and records points in the same order as in the **record points** procedure.

4. **Print a file**: At the conclusion of a series of measurements, the subject's data are printed on his or her data form. In order to do this, the **print a file** procedure first displays a list of the names of the existing data files, from which the operator selects one to print. When the file has been printed, the program returns to the main menu.

5. **Display Subject.Num file**: Each subject's data disk contains a file named "Subject.Num" which includes the subject's sex and subject number. The program reads this information from the subject's disk in Drive B in order to create AHD data file names and to facilitate data analysis. This menu item displays the "Subject.Num" file in the upper half of the screen, so that it may be checked if necessary.

6. **Display machine coordinates**: This item is used primarily in testing the operation of the CMS encoders. It should be used if inaccuracies in calibration and/or scaling persist (e.g., numbers change radically, or fail to change at all when the probe is moved around). Normally, during measurement, the X and Y coordinates displayed are linear horizontal distances forward of and lateral to the center of the back headboard; these are rectangular coordinates calculated by the program from information provided in polar coordinates by the encoders. During the **display machine coordinates** operation, the X and Y coordinates displayed are those relative to the center of rotation of the system and not the headboard surfaces. Therefore, the information is not displayed in terms of X and Y, but rather in terms of the polar coordinate system in which radius r is always associated with the position of the horizontal slide, and angle $\phi$ always describes the position of the rotary encoder. With respect to the BEGIN-END position in both the rectangular and polar systems, the Z axis is associated with the vertical distance encoder.

Since the output of each encoder is examined individually, failure of any one of the encoders can be noted immediately. Movement of the CMS probe along any of the axes should cause the value appearing in the monitor display to change. If no such changes are observed for a particular movement, the encoder for that axis may be defective. Such information is important and should be reported to the design engineer promptly.

7. **Terminate program**: This item ends the program, returning control to the DOS. It should be executed before the computer is turned off. Although the program may be terminated between subjects during a measurement session, this is not recommended because it will require time-consuming recalibration of the machine when the program is started again.

## CALIBRATING THE CMS

Whenever the AHD program is started, the **calibrate** procedure must be performed. During measurement sessions, periodic calibration checks should be made. Calibration can be verified throughout the day in the following way:

Visually check the XYZ coordinates on the monitor when the arm is in the BEGIN-END position. The following values -- ± 2 mm* -- should be displayed:

**X = 60**

**Y = -216**

**Z = 13**

If the displayed values are within limits, the calibration is assumed to be good. Any values which fall beyond these limits indicate the need for recalibration.

The purpose of the calibration procedure is to install precise scaling factors into the main program memory. Two support rods and a special fixture are used. The software has "prior knowledge" of certain aspects of the fixture relative to the two reference planes when it is properly positioned. Before installing the rods, the head stabilization clamp is closed so that the distance between the arms of the clamp is at a minimum in order to clear the bushings for insertion of the rods. Turn the head clamp control knob to tighten (see Figure D-6). Next, the support rods are screwed into the bushings on the bottom surface of the support housing as indicated in Figure D-13.

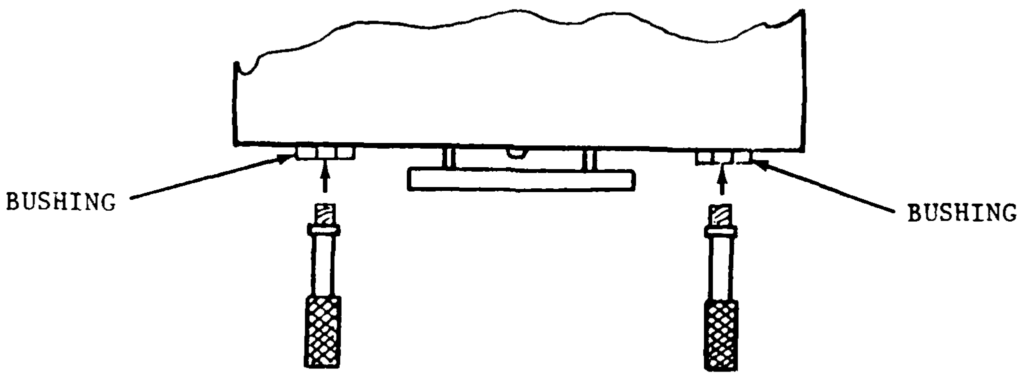



Figure D-13. Support rods in position for installation.

The location of the two bushings is also shown in Figure D-14. The rods should be screwed into the bushings until they are finger tight.

---

* The ± 2 mm is principally related to the inability to restore the exact BEGIN-END position each time. The Z axis is likely to be the most variable since the stop is padded with rubber. The compressibility of the rubber may vary with temperature, hence affecting the absolute position of the vertical slide when at rest on the stop. The Z axis calibration value may also be affected by variation in the stylus positioning.

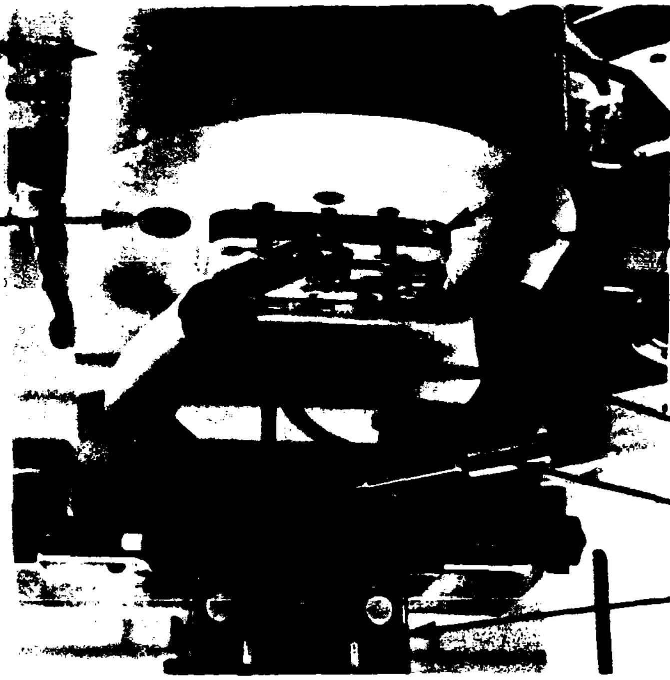



Figure D-14. Front view of the rotary support housing showing locations of bushings where calibration rods are installed.

Once the rods are in place, the next step is to position and secure the fixed radius fixture (see Figure D-15). The fixed radius fixture is machined from two, half-inch thick aluminum plates. One plate includes portions of a circle of precisely known diameter (diameter = 164.846 mm, radius = 82.423 mm). This plate is attached to the second or mounting plate of the same thickness and material. As indicated in Figure D-15, the fixture has been labelled to assist in the installation process. Because the fixture must be installed exactly the same way on each occasion, use the procedure outlined below:

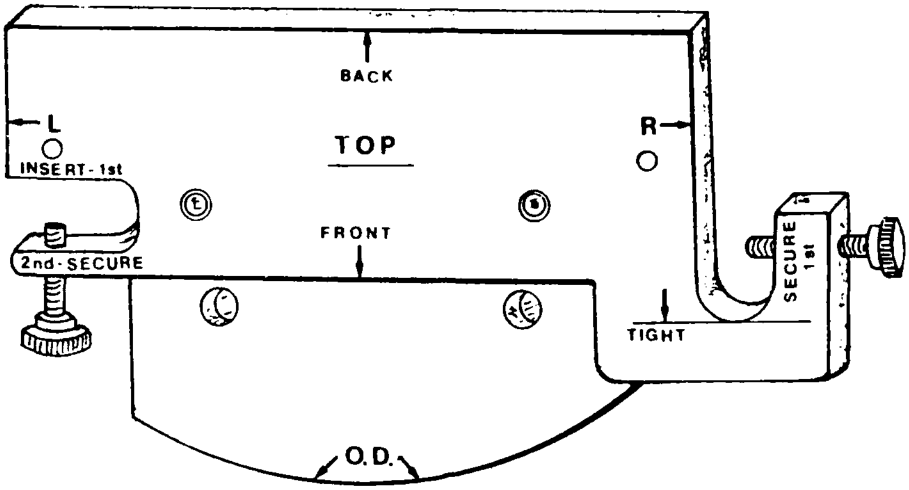



Figure D-15. Top view of the fixed radius fixture.

1. Loosen the thumb screws so that the two cutouts on the fixture are clear of the protruding set screw.

2. Orient the fixture with the top side up and insert the left-hand cutout onto the rod on the left. Move the fixture left until the right-hand cutout can be slipped onto the rod on the right.

3. With both rods in their respective cutouts, position the right side tight against the rod and raise the fixture until the top headboard is tight against its stop.

4. Next, align the fixture so that it is flush with the top headboard surface while the headboard is tight against its stop. Check for fixture/headboard contact over the respective surfaces and then tighten the right-hand set screw on the rod.

5. Without allowing the fixture to move, tighten the left-hand set screw on its rod.

6. Check the fixture/headboard alignment and readjust as necessary.

The calibration equipment (including an earlier version of the support rods) is shown after installation in Figure D-16.

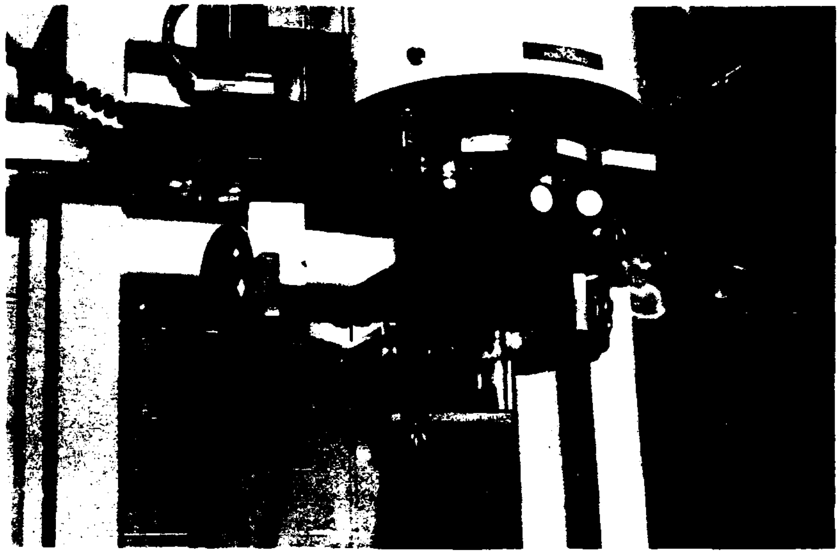


Figure D-16. Front view of the headboard area showing the calibration equipment in place.

When the fixture has been properly installed, the **calibrate** procedure can be completed. The monitor will display the prompt: **set axes to fixture? (y/n)**. Respond by entering "Y" for yes. The display will return the prompt: **take a point on the od* of the fixture.**

Unlock all three axes of the CMS and proceed to touch the bead to the curved portion on the front center of the fixture. If an AUTO-TRIP probe is used (switch on the computer peripherals panel in the UP position), the point will be entered automatically when the surface is touched. If the same switch is DOWN, the point may be manually recorded by depressing the switch on the remote hand-trip box while the bead is in contact with the fixture "od" surface. When the point is recorded, a beep will sound and the display will update and appear as follows:

**take a point on the bottom of the fixture**
**current radius is 10.000****
**radial offset is 100.00****

---

* od here refers to the "outside diameter" of the curved aspect of the fixture.

** Sample values.

As instructed, contact or touch the probe to the bottom surface of the fixture by maneuvering the head into position. When the point is recorded, the computer will beep and the display will change to read:

**x [3] is 114.7*        8.030***
**Z offset is 180.0200.523***
**PRESS ENTER TWICE TO PROCEED TO MAIN MENU**

When ENTER is depressed, the calibration is complete and the program will return to display the original menu. Return the CMS arm to the BEGIN-END position and lock the axes. The XYZ values should read within the limits given earlier: x = 60 ± 2 mm; Y = -216 ± 2 mm; Z = 13 ± 2 mm. Remove the fixed radius fixture and the support rods and return them to their storage box.

## PREPARATIONS FOR MAKING THE MEASUREMENTS

### Preparing the computer

1. When a subject arrives, insert his/her disk in Drive B.

2. Select item #2, **record points**, from the menu. The first thing the computer checks is the sex variable in the "Subject.Num" file on the subject's disk. Provided that the subject is the same sex as the previous subject, you will not be aware that the computer is doing this. However, if there is a change -- if this is the first subject after the AHD program was started, or if the previous subject was of the opposite sex -- the computer will display a message to verify the current subject's sex, for example:

   **Now measuring MEN.**

   **OK?                (y/n)**

   If you respond with "N", "n", or "-", the program will inform you that there may be something wrong with the subject's disk, and eventually return you to the main menu. From the menu you should use option #5 **(display Subject.Num File)** to try to determine the problem. A response of "Y", "y", or "+" leads to a request for the subject's number.

3. Type the subject number, with or without leading zeros, and press "<return>." The program responds with a check on the number you entered, for example:

   **Subject number** 12345.

   **OK?                (y/n)**

   Responding "N", "n", or "-" gives you a chance to re-enter a mistyped subject number. Responding with "Y", "y", or "+" leads to the **record points** procedure.

---

* Sample values.

4. As the **record points** procedure comes up, the top portion of the screen will appear as follows:

| | |
|---|---|
| X | 60 |
| Y | -216 |
| Z | 13 |

**FILE: B:SN01441.YS***
**Press <s> to close file**
**Press <*> to cancel last point taken**
**Press <!> to abort point recording**

**MALE***

**1. R Tragion**

The numbers appearing in the XYZ graphic depend upon the current position of the touch probe bead; however, the CMS arm should be in the <u>BEGIN-END</u> position.

The number and name of each successive landmark to be measured will appear on the monitor. "R Tragion", shown above, indicates the first point to be measured. R and L refer in this case to the subject's right and left, not the operator's!

In order to hand trip the points, the recorder must make sure the small switch on the CMS computer peripherals panel is in the "down" position. This will activate the remote hand switch box. A small red light on the box indicates that the switch is activated.

<u>Final preparations - AHD</u>

While the recorder prepares the computer, as outlined above, the operator prepares the AHD to receive the first subject. The recommended steps are outlined below:

1. THE ARM OF THE CMS SHOULD BE IN THE <u>BEGIN/END</u> POSITION!

2. Depress the DOWN button on the seat control on the right arm of the chair and lower the seat to <u>near</u> the bottom limit. Try to stop the seat drive motor before the bottom limit is reached. A clicking sound will be heard when this happens. Repeatedly running the motor against the stops (at either end) may ultimately damage the motor.

3. Clean subject contact surfaces such as the headboard surfaces, the head clamp pads, the touch probe bead, and the chair arms with an alcohol swab. Repeat the alcohol cleaning procedure between each subject.

---

* Sample subject number and sex.

4. Since the head clamp may be in the calibration position (fully in), open the head clamp widely enough to clear the subject's head easily.

5. Recheck the HEAD-POSITION lights by fully depressing both headboards simultaneously.

6. Place the foot rest in position by slipping the end "cutouts" over the front rail of the support frame.

## Preparing the Subject

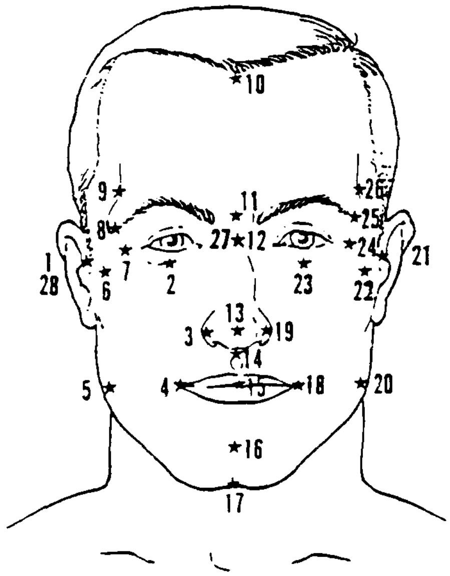
The nature and purpose of the procedure must be described briefly to each subject as he or she reports to the station. This orientation may be given by either member of the team, and it may be completed while the landmarks are being drawn.

Coordinates for a total of 26 drawn landmarks are to be measured with the AHD in the 1987-1988 Army Survey. Some of these (tragion, right and left; infraorbitale, right; crinion; sellion; and menton) will already have been drawn on the subject's face for other head/face measurements and must be checked. An additional 20 landmarks, listed in Table D-1, and shown on Figure D-17, must be placed on the subject's face by the operator at the headboard station. Using a surgical marking pen, place small dots (no larger than 2 mm in diameter) to mark all the remaining landmarks.

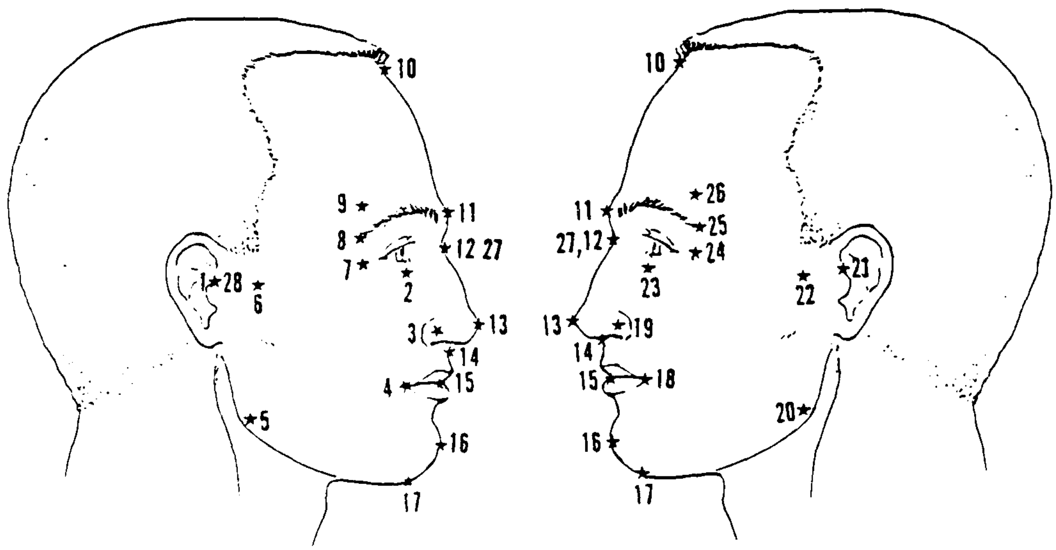
The list in Table D-1 is organized in the order in which coordinates are to be measured. Points #27 and #28, it will be noted, are repeats of points measured earlier. The order of measurements was designed to minimize the number of passes about the subject's eyes and to offer the shortest route of travel between successive points. The software for this survey was designed to accept the points only in the order listed.

TABLE D-1. List of Landmark Locations in Order of Measurement.

| | | | |
|---|---|---|---|
| 1. | R Tragion | 15. | Stomion |
| 2. | R Infraorbitale | 16. | Promenton |
| 3. | R Alare | 17. | Menton |
| 4. | R Cheilion | 18. | L Cheilion |
| 5. | R Gonion | 19. | L Alare |
| 6. | R Zygion | 20. | L Gonion |
| 7. | R Ectoorbitale | 21. | L Tragion |
| 8. | R Zygofrontale | 22. | L Zygion |
| 9. | R Frontotemporale | 23. | L Infraorbitale |
| 10. | Crinion | 24. | L Ectoorbitale |
| 11. | Glabella | 25. | L Zygofrontale |
| 12. | Sellion | 26. | L Frontotemporale |
| 13. | Pronasale | 27. | Sellion (repeat) |
| 14. | Subnasale | 28. | R Tragion (repeat) |



1. R Tragion
2. R Infraorbitale
3. R Alare
4. R Cheilion
5. R Gonion
6. R Zygion
7. R Ectoorbitale
8. R Zygofrontale
9. R Frontotemporale
10. Crinion
11. Glabella
12. Sellion
13. Pronasale
14. Subnasale
15. Stomion
16. Promenton
17. Menton
18. L Cheilion
19. L Alare
20. L Gonion
21. L Tragion
22. L Zygion
23. L Infraorbitale
24. L Ectoorbitale
25. L Zygofrontale
26. L Frontotemporale
27. Sellion (<u>repeat</u>)
28. R Tragion (<u>repeat</u>)



SUBJECT'S RIGHT SIDE | SUBJECT'S LEFT SIDE

Figure D-17. <u>The landmark locations and the order of measurement of coordinates.</u>

Positioning the Subject

The following conditions should exist at this time: The CMS arm in the BEGIN-END position, the seat in a low position, and the head clamp wide open. The steps for positioning the subjects for measurement are outlined below.

1. Instruct the subject to be seated. Determine the required size of safety glasses (large-wide or small-narrow) and assist the subject in positioning the glasses on the face. The lenses are plastic and not vision-corrective.

2. Ask the subject to relax when fully seated. Encourage the subject to assume a slightly slumped position.

3. Ask the subject to operate the chair lift by depressing the UP button located in the arm of the chair on the subject's left. As the chair ascends, guide the subject's head into position by gently holding it by the sides and sliding it against the rear headboard surface.

4. As the subject's head contacts the top headboard, the chair will automatically stop. Reassure the subject that this will happen.

5. The two small red HEAD POSITIONED lights on the lower front aspect of the rotary support housing should now be lighted. Manually align the subject's head as nearly as possible into the Frankfort plane (Figure D-18). It may be necessary for the subject to sit more erect and to make a conscious effort to keep the head pressed against the reference planes in order to keep the lights lighted throughout the measurement procedure. The lights indicate that the headboard pieces are at right angles and that the head is fully in contact with both surfaces.

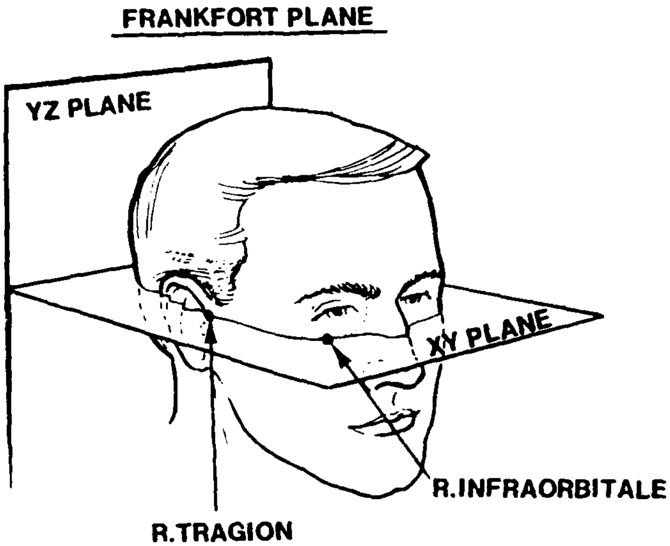



Figure D-18. Frankfort plane.

6. Ask the subject to hold the position while you loosen the rotary locking knob and the vertical axis locking knob of the CMS. See Figure D-6 and Figure D-7, respectively.

7. Unlock the horizontal slide and position the bead directly on the R Tragion landmark. With the bead still aligned with the landmark, lock the vertical axis and quickly swing the arm to check the Z level of the R Infraorbitale landmark. If infraorbitale is above or below tragion level by more than a few millimeters, ask subjects to lower or raise their heads accordingly and hold the position while you recheck R. Tragion and alignment along the XZ plane, i.e., L. Infraorbitale should be at the same level as R. Infraorbitale. After the Frankfort plane is established, position the arm out of your way and as quickly as possible tighten the head clamp by turning the control knob CCW. Ask the subject to tell you when the clamp is snug, but not uncomfortable. Make sure the "HEAD POSITIONED" lights are on as the clamp is tightened.

8. When you are satisfied that the head position is correct and the lights are on, make sure that the AUTO/MANUAL trip switch on the computer peripherals panel is in the "down" position.

9. Make sure the subject's diskette has been inserted in disk DRIVE B. You are now ready to measure coordinates.

## MEASURING COORDINATES

### Collecting and Processing the Data

After the subject's head has been properly positioned and secured, loosen the locking knobs on all three axes. The CMS is now free to move from point to point. Following the order listed in Table D-1 and shown on the monitor, maneuver the CMS arm around, in and out, and up and down as necessary, to gently touch each landmark in succession. Do not dimple the skin any more than necessary to ensure that contact is established. When you are sure that you have the bead centered on the landmark to be measured, instruct the recorder to depress the hand switch in order to record the coordinates. The recorder may assist by naming aloud each landmark as it appears on the monitor screen.

Since the possible ways you may contact a given landmark are dictated by the degrees of freedom of movement in the CMS arm, each point will generally be touched in the same manner on all subjects. For example, the bilateral landmarks on the right and left side of the face are typically contacted on the inner (toward the subject) aspect of the bead. Those lying on the midsagittal line, or nearly so, are touched with the tip of the bead or topmost aspect of the bead as follows: those touched with the tip of the bead include crinion, glabella, sellion, pronasale, stomion, and promenton; subnasale and menton are approached by coming up from below the landmark and are, therefore, contacted with the topmost aspect of the bead. The software includes corrections for the bead diameter (remember that the bead center is the zero calibration point) and the direction of contact. Therefore, it is important to touch landmarks as instructed in order to get accurate measurements. With practice, operators learn to move from point to point

quite easily and rapidly; however, it is important to remember at all times not to frighten or injure a subject. Obviously, this is particularly true while working around the eyes.

If a point is recorded erroneously, the XYZ values may be deleted by depressing the "*" key on the keyboard. The erroneous values are automatically cleared and the point is remeasured. When all points are recorded, the program will not accept any more.

Close the file by pressing the "s" key. The program will take several seconds to analyze the data in the file. During this time the subject should remain in position, unless he/she has already been measured twice. The program will display a message indicating whether the measurements were **good** (all points reasonably located with respect to one another) or not.

If all the points in the first set of measurements were good, the message remains on the screen while the program writes two additional files on the subject's disk. The program prepares itself for another operation and returns to the main menu.

If one or more points from the first set of measurements are found to be out of range, the program will ask that the subject be remeasured. The entire set of measurements is repeated since, if the subject has moved between measurements, the location of a single remeasured point would probably not be within editing range with respect to the points in the original data set.

When remeasurement is required, the program does not return to the main menu, but instead goes back to the **record points** display of XYZ graphic, file name and commands, and the prompt for R. Tragion. Before starting the remeasurement, verify that the subject's head is still in the Frankfort plane.

To print the subject's data file on his/her disk, select option #4, **print a file**, from the main menu. The program will provide a numbered list of the available data files (in most cases, there will be only one). Enter the number of the file to be printed, or enter "*" to return to the main menu without printing anything. Check the printer to be sure that it is on-line (an orange light on the printer control panel will be lit) and that the subject's data form is properly inserted. When everything is ready, press "<enter>" once more to start printing.

After the file is printed, the program returns to the main menu.

## Dismissing the Subject

Upon successfully completing all the measurements, the subject is ready to be released. The following steps should be followed:

1. Position the CMS arm in the BEGIN-END position. (This will permit the chair to be lowered.) With the arm tight against the stop/interlock switch, tighten the rotary locking nut. Withdraw the horizontal slide to the stop and tighten the locking nut. Raise the arm against the vertical slide stop and tighten the locking nut.

2. Loosen the head clamp to the full open position. Help the subject to remove the safety glasses.

3. Have the subject depress the chair DOWN button. Assist the subject to clear the clamp-headboard area, and help him/her from the chair.

4. Present the subject with his/her diskette and the data blank on which the data have been printed.

5. Clean the contact surface in preparation for the next subject.

6. Check the BEGIN-END values displayed on the monitor. If X, Y, or Z are outside the range listed, recalibrate the CMS in preparation for the next subject.

Disassembling the AHD for shipment

Upon completion of the measurements at a given site, the AHD must be disassembled and prepared for shipment. The procedure is basically the reverse of the setup process. The recommended procedure includes the following sequence of steps:

1. Disconnect all power sources and the computer cable from the AHD.

2. Remove the touch probe and place in its shipping container. Position the horizontal slide in mid-position and lock.

3. Lift and align the vertical axis assembly (arm) with the safety bolt access hole (see Figure D-19). Using a 1/4" Allen wrench and by turning the bolt CCW, run the safety bolt into the horizontal axis assembly until it is securely locked into position. Tighten the locking nut.

4. Using a 5/16" Allen wrench, loosen and remove the four bolts that attach the horizontal axis assembly (see Figure D-10). Disconnect the encoder cable (see Figure D-10).

5. Carefully remove the assembly from its alignment pins and place the assembly into its shipping container. Position the foam rubber packing. Close and latch the lid. Some assistance may be required to remove and pack the assembly.

6. Lock the rotary and, using a 5/16" Allen wrench, loosen and remove the four bolts that secure the vertical axis assembly (see Figure D-19). Disconnect the computer cable at the junction box (see Figure D-19). Carefully remove the assembly from its alignment pins and place it into its shipping container. Since the assembly weighs over 20 pounds, you should ask for assistance to handle it safely. Position the foam rubber padding and latch the container lid in place.

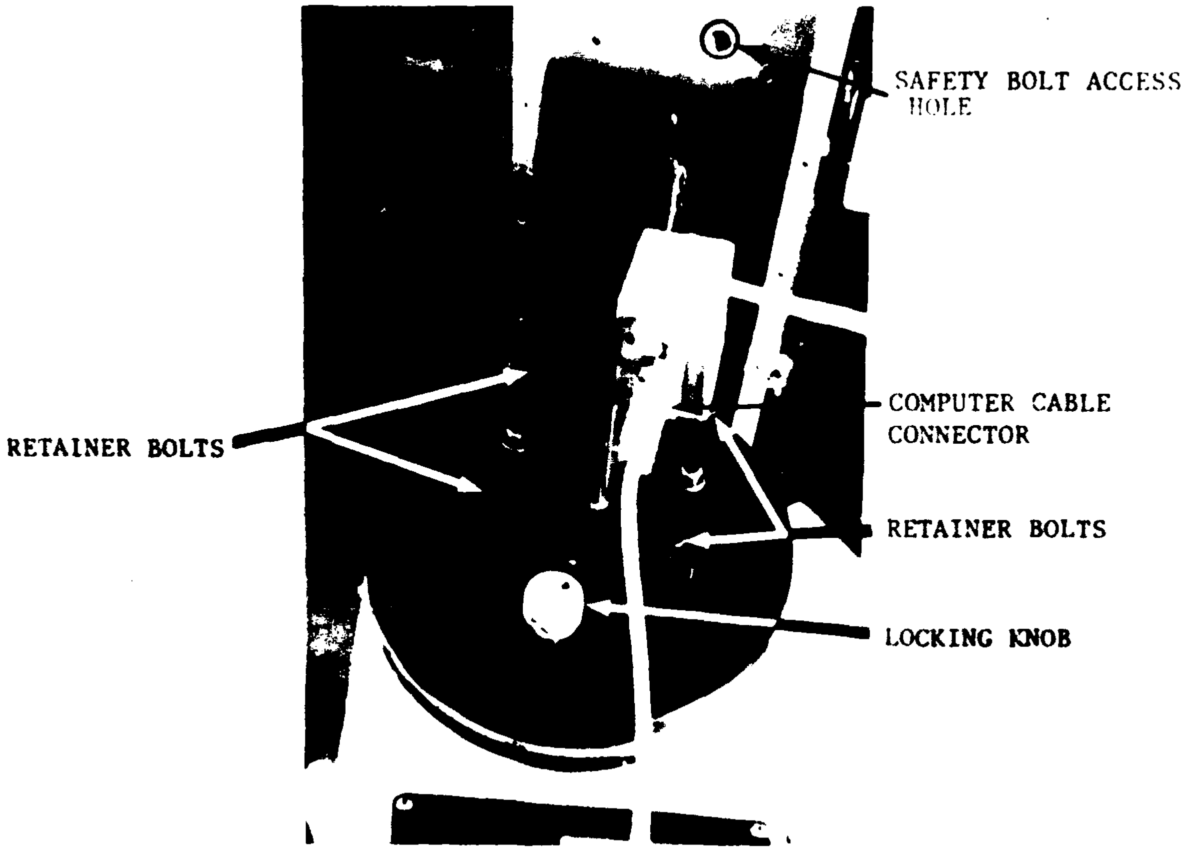



Figure D-19. Rotary bearing area showing the retainer bolts, the computer cable, and safety bolt access port (see also Figure D-8).

## CARE AND MAINTENANCE

Although the AHD was ruggedly constructed for use in field survey conditions, it contains a number of very delicate and sensitive features. Most of these features are associated with the CMS and in order for the device to continue to provide reliable and accurate measurement of 3-D coordinates over an extended period of time, the operators should perform a number of routine maintenance tasks. Some aspects of the maintenance will need to be performed daily; others will only be required periodically. Lists of these tasks are given below. Also provided are lists of the items included in the tool kit, the supplies, and the replacement parts and accessories provided with the AHD.

### Daily

When setting up, and each day during operation, the following routine maintenance should be performed using the equipment supplied:

1. Wipe clean the horizontal slide bar and the vertical slide rails (see Figures D-7 and D-10) with a clean, dry, lint-free cloth to remove fingerprints.

2. Once clean, apply a light coat of machine oil and wipe the surface with a lint-free cloth.

3. Using one of the small brushes provided, sweep any debris from the racks for both slides. This will help to ensure smooth operation of the encoder pinion gears.

Periodic

1. Inspect all encoder cables and their connectors. Any evidence of wear or impending failure should be reported to the design engineer.

2. Inspect and replace, as needed, the foam padding on the head stabilization clamp. Remove the worn pads and use them to size the replacement pads. Simply slip the padding off or on the head clamp arms. Save and reuse the plugs for the front end of each pad.

3. Check the CMS, chair lift, and other moving parts for proper operation before the first subject of the day arrives at the station. Make corrections and repairs as needed. Contact the design engineer if assistance is required.

4. Check the headboard angle as the HEAD POSITIONED lights come on using the plastic triangle from the tool kit. The headboard surfaces should be positioned at 90° when they are against their stops. If the angle is visibly more or less than 90°, adjust the stop screws using a 1/8" Allen wrench until a right angle is reestablished. Make sure the HEAD POSITIONED lights are on when the headboards are against their stops. The stop set screws also serve as the contact switches for these lights.

5. Vacuum chair pads.

6. Inspect all calibration equipment for wear. Repair and/or replace as necessary.

7. Polish the exposed surfaces of the slide assemblies to remove any aluminum oxide build-up. Use the aluminum polish supplied and a rag. Do not use the same rags used for cleaning the slides!

8. Inspect the counter balance cable for wear. Do not replace this yourself. Notify the design engineer if replacement is required.

9. Generally clean and dust the AHD frame.

Tool Kit

1 - set of Allen wrenches - 1/32" thru 3/8"
1 - set of small screwdrivers
1 - small, medium and large blade screwdriver
1 - medium size Phillips screwdriver
1 - small adjustable wrench, 4" crescent
1 - medium adjustable wrench, 6" crescent
1 - standard pliers, 6"
1 - needle nose pliers
1 - wire cutter, small
1 - solder iron
1 - roll of solder
2 - combination locks (for shipping containers)
1 - height gauge, 30 cm
2 - small cleaning brushes for racks
1 - 6" clamp
1 - box of miscellaneous crimp-ons
1 - crimping tool
1 - pair of scissors
1 - plastic drafting triangle

Supplies

6 - lint-free cleaning cloths
1 - can of light machine oil
1 - can of teflon spray
1 - can of silicone
1 - container of aluminum polish
25 ft. of braided grounding strap
1 - 25 ft. power cord, with ground
1 - 100 ft. power cord, with ground
miscellaneous cleaning brushes
2 - 12 oz. bottles of 70% ethyl alcohol
2 - packages of 2" x 2" gauze sponges
1 - 4-slot 3-prong power strip
1 - ground fault interruptor
1 - hand vacuum cleaner
neoprene foam insulation tubing (head clamp padding)
encoder cable wire

Spare Parts and Accessories

1 - printed circuit board (CMS computer board)
1 - Spaulding encoder
1 - set of calibration fixture support rods, spare
1 - touch probe, spare
1 - replacement thumb screw for calibration fixture
2 - miniature lights, 12 volts DC, (HEAD POSITIONED lights)
miscellaneous replacement connectors for encoder cables
1 - 1-cm thick rear headboard spacer block
1 - set of AHD blueprints with parts lists

Spare Parts and Accessories

1 - spare computer cable
1 - foot rest
2 pairs - safety glasses (large and small)

## APPENDIX E.

Main Computer Program

```
Program dro(input, output);
(****  modified edition:  1/21/88  Bill Anderson/Jo Ross
                          2/15/88  Jo Ross                    *********)
{$C-}

{$U-}

{$B-}

{$V-}

const    CK = 4.0;                {Check value for number of standard
                                   deviations}

         current = 532;

         c_offset = 6.777;

         debug = false;           {set "true" for debug version of the program,
                                   which incorporates several tests and error
                                   messages.}

         dro_y = 2;               {used to locate top of graphic display of
                                   XYZ coordinates on second line of screen}

         ext = '.YS';             {extension for subject data filenames}

         gagefile = 'a:gage.prm'; {name of file containing calibration data}

         gage_dia = 164.846;      { 6.490 inches; diameter  of gage}

         has_counters = true;

         namefile = 'a:points.txt';   { contains names of points to measure }

         num_names = 30;          {maximum number of names of landmarks; 26 used}

         nvs = 26;                {number of landmarks measured}

         old_counters  = true;

         pi = 3.1415926525;

         places = 1;

         probe = 548;

         rcomp = 1.0;             {compensation factor for offset of probe bead;
                                   bead radius is 1 mm}

         top_of_bottom = 8;       {line #8 is the top line in the bottom section
                                   of the screen}
```

```
    y_offset = 88.1;        {distance from backboard to center of rotation}

    z_gage = 24.4;



TYPE
  vector = array[1..3] of real;
  rec = packed array[1..38] of char; {9 per axis + 9 spaces + cr + lf}
  string80 = string[80];
  string20 = string[20];
  s5 = string[5];
  s2 = string[2];
  s1 = string[1];
  rec_file_type = file of rec;
  ai283222 = array[1..28,1..3,1..2,1..2,1..2] of integer;
  ar282r = array[1..28,1..2] of real;
  ar28372r = array[1..28,1..3,1..8,1..2] of real;
  ar283r = array[1..28,1..3] of real;
  ar28r = array[1..28] of real;
  ar2832r = array[1..28,1..3,1..2] of real;
  vec32 = array[1..3,1..2] of real;
  vec42 = array[1..4,1..2] of real;
  mat332 = array[1..3,1..3,1..2] of real;
  mat442 = array[1..4,1..4,1..2] of real;
  ar2632r = array[1..26,1..3,1..2] of real;
  vec3 = array[1..3] of real;
```

```
ar5i = array[1..5] of integer;

s4 = string[4];

s9 = string[9];

ar28c = array[1..28] of string[20];

ar263r = array[1..26,1..3] of real;

ars250 = array[1..3] of string[80];

ar2r = array[1..2] of real;

str66=string[66];

str255=string[255];

s3=string[3];

s11=string[11];



VAR
    dro1,
    dro2,
    dro_x,
    dummy_count,
    error,
    number,
    num_points,
    scxmax,
    subno,subno1,
    i, IS,J,M,X,NT : integer;

    name : array[1..num_names] of string80;

    comp : array[1..num_names,1..3] of integer;

    current_radius,
    current_angle,
    deg_to_rad : real;

    final_mat : array[1..3,1..3] of real;

    z_offset, radial_offset : real;

    names : array[1..3] of string80;

    off,                                {Variable "off" corrects for motor noise.}
    apreset,
```

```
   counts : vector;


   before_first_point,
   bridge,
   dro_destroyed,
   file_name_made,
   foot_switch,
   init_complete,
   machine_system,
   map,
   proc_complete,
   program_end,
   repeat_command,
   replace_sn,
   RETEST,
   REMEASURE,
   skip_regression,
   calibrated : boolean;


   filename,
   SNFILE,
   original_sn,
   old_sn,
   temp_file,
   retest_file,
   oldata : string20;

   prefix : s2;

   snow : s5;

   charsex, gender_string,
   repeat_command_chr : char;

   IVN : ai283222;

   SE : ar2832r;

   EQC : ar28372r;


(* The following two lines are compiler directives which instruct the compiler
   to include the Pascal code from two other files when compiling the main
program.
   Storing segments of code in other files is necessary to overcome memory size
   limitations set by Turbo Pascal version 3.0.
 *)

{$I a:INITREG.PAS }

{$I a:REGROT.PAS }
```

```
(*-------------------------------------------


--------------------------------------------*)
procedure beep;

(* Purpose:  Produces sound from monitor to call operator's attention to the
   screen; to be called from error-checking procedures when the operator needs to
   be warned.
 *)

begin
     SOUND(700);
     DELAY(500);
     NOSOUND;
end;
(*-------------------------------------------


--------------------------------------------*)
procedure get_int_str (count : integer;
                      var s : string80);

(* Purpose: Reads subject number from keyboard.  Procedure Get_Subno asks the
   operator to enter the subject number, then calls this procedure.  Procedure
   get_int_str accepts only characters '0' thru '9', backspace and carriage
   return; it does not accept letters.
        "Count" is the number of digits to be entered
        "S" is the string which is filled with the subject number
 *)

var
     ch : char;

     x, y, i,
     chrs_entered : integer;

     done : boolean;

begin
     x := wherex;
     y := wherey;
     s := '';
     for i := 1 to count do begin
          insert (' ', s, 1);
     end;
     chrs_entered := 0;
     gotoxy (x, y);
     write (s);
     done := false;
```

```
    repeat
        repeat
            read (kbd, ch);
        until ch in ['0'..'9', chr (13), chr (8)];

        case ord (ch) of
            48..57 : begin
                if chrs_entered < count then begin
                    insert (ch, s, count + 1);
                    chrs_entered := chrs_entered + 1;
                    delete (s, 1, 1);
                    gotoxy (x, y);
                    write (s);
                end;
            end;

            8 : begin
                if chrs_entered > 0 then begin
                    insert (' ', s, 1);
                    delete (s, count + 1, 1);
                    gotoxy (x, y);
                    write (s);
                    chrs_entered := chrs_entered - 1;
                end;
            end;

            13 : begin
                done := chrs_entered > 0;
            end;
        end;
    until done;
    while s [1] = ' ' do begin
        delete (s, 1, 1);
    end;
end;
(*--------------------------------------------



--------------------------------------------*)
procedure Key2Continue;
(* Purpose: Used to delay program until  the operator responds.
*)

var
    ch : char;
begin
    repeat
    until keypressed;
    read (kbd, ch);
end;
(*--------------------------------------------
```

```
---------------------------------------------*)

  (* * * * * * * * * * * * * *  N O T E  * * * * * * * * * * * * * * * * *)
  { Functions BROTATE and WROTATE correct a problem in the layout of
    the counter printed circuit board;  namely, that the data bus was
    wired backwards --- bit 7 was wired to bit 0, bit 6 to bit 1, and so on. }
  (* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *)

function brotate (i : integer) : integer;

(*
     Purpose :  Reverses the bits in a byte.

*)

begin
   inline($8b/$5e/$04/            { mov bx,[bp] + 4 }
   $b8/$00/$00/                   { mov ax, 0000 }
   $d0/$db/$d0/$d0/         { rcr bl,1     rcl al, 1 }
   $d0/$db/$d0/$d0/         { rcr bl,1     rcl al, 1 }
   $d0/$db/$d0/$d0/         { rcr bl,1     rcl al, 1 }
   $d0/$db/$d0/$d0/         { rcr bl,1     rcl al, 1 }
   $d0/$db/$d0/$d0/         { rcr bl,1     rcl al, 1 }
   $d0/$db/$d0/$d0/         { rcr bl,1     rcl al, 1 }
   $d0/$db/$d0/$d0/         { rcr bl,1     rcl al, 1 }
   $d0/$db/$d0/$d0/         { rcr bl,1     rcl al, 1 }
   $89/$ec/
   $5d/
   $c2/$04/$00)                  { mov [bp] + 4, bx}
end;
(*---------------------------------------------



---------------------------------------------*)
function wrotate (i : integer) : integer;

(*
     Purpose :  Reverses the bits in a integer
*)

begin
   inline($8b/$5e/$04/            { mov bx,[bp] + 4 }
   $d1/$db/$d1/$d0/         { rcr bx,1    rcl ax,1 }
   $d1/$db/$d1/$d0/         { rcr bx,1    rcl ax,1 }
   $d1/$db/$d1/$d0/         { rcr bx,1    rcl ax,1 }
   $d1/$db/$d1/$d0/         { rcr bx,1    rcl ax,1 }
   $d1/$db/$d1/$d0/         { rcr bx,1    rcl ax,1 }
   $d1/$db/$d1/$d0/         { rcr bx,1    rcl ax,1 }
   $d1/$db/$d1/$d0/         { rcr bx,1    rcl ax,1 }
   $d1/$db/$d1/$d0/         { rcr bx,1    rcl ax,1 }
   $d1/$db/$d1/$d0/         { rcr bx,1    rcl ax,1 }
   $d1/$db/$d1/$d0/         { rcr bx,1    rcl ax,1 }
```

```
    $d1/$db/$d1/$d0/        { rcr bx,1    rcl ax,1 }
    $d1/$db/$d1/$d0/        { rcr bx,1    rcl ax,1 }
    $d1/$db/$d1/$d0/        { rcr bx,1    rcl ax,1 }
    $d1/$db/$d1/$d0/        { rcr bx,1    rcl ax,1 }
    $d1/$db/$d1/$d0/        { rcr bx,1    rcl ax,1 }
    $d1/$db/$d1/$d0/        { rcr bx,1    rcl ax,1 }
    $89/$ec/
    $5d/
    $c2/$04/$00)                { mov [bp] + 4, bx}
end;
(*--------------------------------------------



----------------------------------------------*)
procedure erase_line ( i : integer );

(*
     Purpose :  Erases line number i, numbering starts with 0.
*)

begin
   gotoxy(1,i+1);
   clreol;
end;
(*--------------------------------------------



----------------------------------------------*)
procedure erase_top;

(*
     Purpose :  Erase the top portion of the screen (lines 1 through 7),
     occupied by the x, y, z machine position display.
     Calls procedure erase_line.
*)

var i : integer;
begin
   for i := 0 to pred( top_of_bottom ) do begin
        erase_line(i);
   end;
end;
(*--------------------------------------------



----------------------------------------------*)
procedure erase_bottom;

(*
     Purpose :  Erases the part of the screen that erase_top
     does not --- line 8 and below.
```

```
    Calls erase_line.
*)

var i : integer;
begin
   for i := 24 downto top_of_bottom do begin
        erase_line(i);
   end;
end;
(*--------------------------------------------------



----------------------------------------------*)
function freeze : boolean;

(*
     Purpose :   The x, y, z machine display freezes when the touch probe
                 or point recording switch is pressed;  this function returns
                 true when this condition occurs.
                 Calls brotate.
*)

var
     i : integer;

begin
    if before_first_point then begin
         freeze := false; end
    else begin
         i := mem[$d800:$200];
         if old_counters then begin
              i := brotate(i);
         end;
         freeze := ( not foot_switch AND odd(i) )
                                   OR
                   ( foot_switch and NOT ODD(i div 2) );
    end;
end;
(*--------------------------------------------------



----------------------------------------------*)
procedure dummy_data(var r : vector);

(*
     Purpose : Generate dummy coordinates for debugging program;
     called only if constant 'debug' is true.
*)

begin
    if not freeze then begin
         dummy_count := succ(dummy_count);
```

```
    end;
    r[1] := 0;
    r[2] := 20.0 * dummy_count / counts[2];
    r[3] := 20.0 * dummy_count / counts[3];
end;
(*--------------------------------------------



---------------------------------------------*)
function fswitch_pressed : boolean;

(*
     Purpose :  Returns true when the point recording switch is activated.

*)

var
     i : integer;
begin
     i := mem[$d800:$200];
     if old_counters then begin
          i := brotate(i);
     end;
     fswitch_pressed := ODD(i div 2);
end;
(*--------------------------------------------



---------------------------------------------*)
procedure write_at(x,y : integer; s : string80);

(*
     Purpose :  Writes the string s at row y and column x;
                first column and row are 0 and 0.
*)

begin
     gotoxy(x+1,y+1);
     clreol;
     write(s);
end;
(*--------------------------------------------



---------------------------------------------*)



function point_available : boolean;

(*
```

```
     Purpose : Returns true when a point has been recorded by the counter
               card, whether by a touch probe fire or switch closure.
*)

var
     i : integer;
begin
     if has_counters then begin
          i := mem[$d800:524];
          if old_counters then begin
               i := brotate(i);
          end;end
     else begin
          i := 0;
     end;
     point_available := i <> 0;
     if i <> 0 then begin
          before_first_point := false;
          foot_switch := i = 85;
     end;
end;
(*--------------------------------------------------



---------------------------------------------------*)
procedure to_part_system ( var xyz : vector );

(*
     Purpose : Converts the angle and radius machine data to
               cartesisan coordinates.
*)

var
     t : vector;
     i,
     k : integer;
     temp : real;

begin      { add offsets to compensate for motor noise }
     for i := 1 to 3 do begin
          xyz[i] := xyz[i] + off[i];
     end;

     current_radius := xyz[2];
     current_angle := xyz[1] * deg_to_rad;  {current_angle is in radians}

     { switched signs 7-8-87 }
     xyz[2] := y_offset - current_radius * sin( current_angle );
     xyz[1] := - current_radius * cos( current_angle );

     {swap x and y }
     temp := xyz[1];
     xyz[1] := xyz[2];
```

```
        xyz[2] := temp;

        for i := 1 to 3 do begin
            t[i] := 0.0;
            for k := 1 to 3 do begin
                t[i] := t[i] + final_mat[i,k] * xyz[k];
            end;
        end;
        for i := 1 to 3 do begin
            xyz[i] := t[i] - apreset[i];
        end;
    end;
    (*-----------------------------------------------



    -----------------------------------------------*)
    procedure read_counts (offset : integer; VAR r : vector);

    (*
        Purpose : Sets r to either the current machine position or
                  the last recorded point, depending on the value of offset.
    *)

        FUNCTION get_axis(o : integer) : real;
        var
            a,
            b : integer;
        begin
        if old_counters then begin
            a := wrotate(memw[$d800:o]);
            b := wrotate(memw[$d800:o + 2]); end
        else begin
            a := swap(memw[$d800:o]);
            b := swap(memw[$d800:o + 2]);
        end;
        if b < 0 then begin
            a := a + 1;
        end;
        get_axis :=  b + 65536.0 * a;
    end;
    (*-----------------------------------------------



    -----------------------------------------------*)
    BEGIN { read_counts }
        if debug then begin
            dummy_data(r);end
        else begin
            r[1] := get_axis(offset) / counts[1];
            r[2] := get_axis(offset + 4) / counts[2];
            r[3] := get_axis(offset + 8) / counts[3];
        end;
```

```
    if not machine_system then begin
        r[1] := r[1] + c_offset;
        r[2] := r[2] + radial_offset;
        r[3] := r[3] + z_offset;
        to_part_system(r);
    end;
END;
(*----------------------------------------------



----------------------------------------------*)
procedure update_dro;

(*
    Purpose :  Updates the x, y, z coordinate display.
*)

const
    maxi = 9999.9;
var
    xyz : vector;
    ss : string80;
    i : integer;
begin
    if freeze then begin { probe fired }
        read_counts(probe, xyz ); end
    else begin
        read_counts(current, xyz );
    end;
    for i := 1 to 3 do begin
        if abs(xyz[i]) > maxi then begin
            if xyz[i] > 0 then begin
                xyz[i] := maxi; end
            else begin
                xyz[i] := - maxi;
            end;
        end;
    end;

    for i := 1 to 3 do begin
        if keypressed then begin
            exit;
        end;
        gotoxy(dro_x + 2, 2 * i + dro_y - 1);
        write(xyz[i] : 8 : 1);
    end;
end;
(*----------------------------------------------



----------------------------------------------*)
procedure get_probe_pt (var p : vector);
```

```
(*
     Purpose : Reads the last point recorded by firing the touch probe
               or hand switch.
*)

var
     i : integer;

BEGIN
     read_counts(probe,p);
     write( chr(7) );
END;
(*-----------------------------------------------



-----------------------------------------------*)
procedure clear_probe;

(*
     Purpose : Clears the flag on the counter card so a new point can
               be recorded.
*)

var
     k : char;

begin
     mem[$d800:$20c] := 0;
     while keypressed do begin
          read(kbd, k);
     end;
end;
(*-----------------------------------------------



-----------------------------------------------*)
procedure box (x1,y1,x2,y2 : integer);

(*
     Purpose : Draws the box for the x,y,z machine display.
*)

var
     i : integer;

begin
     gotoxy(x1+1,y1+1); write( chr(201) );
     for i := succ(x1) to pred(x2) do begin
          write( chr(205) );
     end;
     write( chr(187) );
```

```
    gotoxy(x1+1,y2+1); write( chr(200) );
    for i := succ(x1) to pred(x2) do begin
        write( chr(205) );
    end;
    write( chr(188) );
    for i := succ(y1) to pred(y2) do begin
        gotoxy(x1+1,i+1);
        write( chr(186) );
        gotoxy(x2+1,i+1);
        write( chr(186) );
    end;
end;
(*----------------------------------------------



----------------------------------------------*)
procedure move_dro (i : integer);

(*
    Purpose :  Moves the x,y,z position display to column i;
    calls procedures erase_top and box.

*)

    (*---------------------------*)
    procedure sub (i : integer);
    var
        j : integer;
    begin
        gotoxy(dro_x - 3, dro_y + i+1);
        write(chr(204));
        for j := succ(dro_x - 4) to pred(dro_x + 10) do begin
            write( chr(205) );
        end;
        write(chr(185));
    end;
    (*---------------------------*)

begin
    erase_top;
    dro_x := i;
    box( dro_x - 4, dro_y - 1, dro_x + 10, dro_y + 5);
    sub(1);
    sub(3);
    { vertical separator }

    gotoxy(dro_x+1, dro_y);
    write ( chr(203) );

    gotoxy(dro_x+1, dro_y + 2);
    write ( chr(206) );

    gotoxy(dro_x+1, dro_y + 4);
```

```
    write ( chr(206) );

    gotoxy(dro_x+1, dro_y + 6);
    write ( chr(202) );

    gotoxy( dro_x - 1, dro_y+1);
    if machine_system then begin
        write('A ', chr(186) ); end
    else begin
        write('X ', chr(186) );
    end;

    gotoxy( dro_x - 1, dro_y + 3);
    if machine_system then begin
         write('R ', chr(186) ); end
    else begin
         write('Y ', chr(186) );
    end;

    gotoxy( dro_x - 1, dro_y + 5);
    write('Z ', chr(186) );
end;
(*---------------------------------------------


----------------------------------------------*)
procedure mikedelay;
(*
   Purpose: delays program until operator responds.  Two keystrokes are
   required to properly exit the block in which this procedure is called.
 *)
begin
    gotoxy(11,14);
    writeln('PRESS  ENTER  (TWICE)  TO PROCEED TO MAIN MENU.');
    readln(kbd);
end;
(*---------------------------------------------


----------------------------------------------*)
function  open_text_file ( var f_var : text;
                           var file_name : string20) : boolean;
(*
   Purpose:  Function attempts to open an assumed-existing  TEXT file.  If
   successful, the function sets boolean variable Open_Text_File true.
   This function serves to check both that the file exists and that it
   can be opened as a text file.
*)

begin
    assign (f_var, file_name);
    {$i-} reset (f_var); {$i+}
```

```
    open_text_file := ioresult = 0;
end;
(*--------------------------------------------



---------------------------------------------*)
function open_file ( var f_var : rec_file_type;
                     var file_name : string20) : boolean;
(*
   Purpose:  Function attempts to open an assumed-existing file of type
   rec_file_type.  If successful, the function sets boolean variable
   Open_File true. This function serves to check both that the file exists
   and that it can be opened as a file of rec_file_type.
 *)

begin
    assign (f_var, file_name);
    {$i-} reset (f_var); {$i+}
    open_file := ioresult = 0;
end;
(*--------------------------------------------



---------------------------------------------*)
function create_file ( var f_var : rec_file_type;
                       var file_name : string20) : boolean;
(*
   Purpose: opens a new  file of rec_file_type, named by the character string
   in file_name, to which data will be written.  Boolean variable create_file
   is set true if the file is successfully opened.
*)

begin
    assign (f_var, file_name);
    {$i-} rewrite (f_var); {$i+}
    create_file := ioresult = 0;
end;
(*--------------------------------------------



---------------------------------------------*)
function active_file (var file_str : string20) : boolean;
(*
   Purpose:  Checks subject data file to be sure it can be opened and
   contains 28 lines.  Fewer than 28 indicates an incomplete or aborted
   data file which is erased in order to be replaced.
   Calls function open_file.
*)
var
    file_var : file of rec;
    ex : boolean;
```

```
begin
    if open_file (file_var, file_str) then begin
        active_file := true;
        if filesize (file_var) <> 28 then begin
            erase (file_var);
            active_file := false;
        end; end
    else begin
        active_file := false;
    end;
    close (file_var);
end;
(*-----------------------------------------------


-----------------------------------------------*)
(*
  Includes Pascal code segment "Getgender.pas" in compilation of main program.
*)
{$I A:GETGENDER.PAS }

(*----------------------------------------------


----------------------------------------------*)
procedure record_points;

(*
    Purpose : Records a file of x, y, z coordinates.
    Calls numerous procedures/functions in addition to those internally
    defined.
*)

var
    f,
    g : file of rec;



    ansr,
    key : char;



    num,
    line,
    z : integer;

    c : rec;
    hold : array[1..4] of rec;

    x,
    xd : vector;
```

```
snhold,
holdata : text;


(*---------------------*)
function check_filename : boolean;
(*
     Purpose : Checks to see whether the subject data file already exists,
     and whether or not it can be opened.
*)


begin { check_filename }
     if not retest then begin {not retest}
          if active_file (original_sn) and (not replace_sn) then
          begin {snexists}
               check_filename := false;
               sound(800);
               delay(800);
               nosound;
               clrscr;
               gotoxy(11,4);
               writeln('NOT RETESTING.');
               Gotoxy(11,6);
               writeln('FILE ', original_sn,' ALREADY ESISTS.');
               Gotoxy(11,8);
               write('DO YOU WANT TO REPLACE ',original_sn, ' ?    (Y/N)  ');

               repeat
                    read(kbd,ansr);
                    gotoxy(60,8);
                    writeln(ansr);
               until ansr  in  ['Y','y','+','N','n','-'];

               case ansr of
                    'Y','y','+' : BEGIN
                         erase_bottom;
                         gotoxy(11,12);
                         write('The Old Data file will be renamed ',
                                old_sn,'.');
                         gotoxy(11,13);
                         writeln('Remember this if you want to print this
                                  file.');
                         gotoxy(11,14);
                         writeln('The new data will be recorded under the
                                  filename  ', original_sn,'.');
                         gotoxy(11,16);
                         write('Press <ENTER> twice to resume
                                testing......');
                         readln(kbd);
                         clrscr;
                         skip_regression := true;
                         repeat_command := true;
```

```
                    repeat_command_chr := '2';
                    replace_sn := true;
                    exit;
                END; {Y}

                'N','n','-' : BEGIN {N}
                    gotoxy(11,13);
                    writeln('To retest subject, return to main menu and
                            select  #3.');
                    Gotoxy(11,14);
                    writeln('Press  <enter>  TWICE to proceed to main
                            menu.');
                    readln(kbd);
                    clrscr;
                    skip_regression := true;
                    exit;
                end; {N}
            END; {case}  END {snexists}
        else begin
            check_filename := true
        end;  end  {if not retest}
    else begin {retest = true}
        if not active_file (original_sn) then begin
            if not active_file (old_sn) then begin
                check_filename := false;
                clrscr;
                beep;
                gotoxy(11,12);
                writeln('CANNOT FIND THE FIRST DATA FILE ON THIS
                        SUBJECT"S DISK.');
                gotoxy(11,13);
                writeln('IF HE/SHE HAS NOT BEEN MEASURED, DON"T
                        RETEST.');
                gotoxy(11,14);
                writeln('Press  <enter>  twice to proceed to main
                        menu.');
                readln(kbd);
                skip_regression := true;
                EXIT;
            end; {not odexists}
        end; {snexists}

        if active_file (retest_file) then begin {rexists}
            check_filename := false;
            gotoxy(11,12);
            writeln('A FILE NAMED ', retest_file, ' ALREADY EXISTS.');
            gotoxy(11,13);
            writeln('DON"T RETEST THE SAME SUBJECT A SECOND TIME.');
            gotoxy(11,14);
            writeln('Press  <enter>  twice to proceed to main menu.');
            readln(kbd);
            skip_regression := true;
            EXIT;end {rexists}
        else begin
```

```
                check_filename := true;
            end; {retest}
        end;
end;
(*----------------------*)



(*----------------------*)
procedure write_prompt;
(*
        Purpose : Writes the name of the next point to be taken.
         Calls procedure write at.
*)
var
        s : string80;
begin
        num := succ( num );
        if num <= num_points then begin
            str(num,s);
            while length(s) < 4 do begin
                insert(' ',s,1);
            end;
            s := concat( s, '. ',name[num], ':' );
            write_at(5,line,s);
        end;
end;
(*----------------------*)



(*----------------------*)
procedure write_point;
(*
        Purpose : Formats the x, y and z coordinates and writes to the screen.
*)
var
        i : integer;
        s,
        ss : string80;

        (*----------------------*)
        procedure scroll_bottom;
          (* Purpose:  Scrolls bottom portion of screen one line each
             time a point is recorded, so that the 16 most recent points
             are displayed.
                    Presently, top_of_bottom := 8; designates the uppermost
                    line of the scrolling portion.
          *)
        begin
            gotoxy(1,top_of_bottom + 1);
            delline;
        end;
        (*----------------------*)
```

```
begin    {write_point}
     s := '';
     for i := 1 to 3 do begin
          str(x[i]:9:places,ss);
          while length(ss) < 12 do begin
               insert(' ',ss,1);
          end;
          s := concat(s, ss);
     end;
     write_at(35,line,s);
     if line = 24 then begin
          scroll_bottom; end
     else begin
          line := succ(line);
     end;
     for i := 1 to 36 do begin
          c[i] := s[i];
     end;
     case num of
        1 : begin
            hold[1] := c;
            end;
        28: begin
            hold[2] := c;
            end;
        12: begin
            hold[3] := c;
            end;
        27: begin
            hold[4] := c;
            end
      end; {case}

     write(f,c);
end;   {write_point}
(*----------------------*)



(*----------------------*)
procedure cancel_point;
(*
     Purpose : Backs up one record in file f, and erases one line from
     the screen.
     Calls procedures erase_line and write_prompt.
*)

begin
     num := num - 2;
     seek(f,num);
     if line > top_of_bottom then begin
          erase_line(line);
          line := pred(line);
```

```
            erase_line(line);
        end;
        write_prompt;
    end;
    (*---------------------*)


    (*---------------------*)
    procedure comp_point;
    (*
        Purpose : Corrects the recorded point for the probe radius.
    *)
    var
        j : integer;
    begin
        for j := 1 to 3 do begin
            x[j] := x[j] + comp[num,j] * rcomp;
        end;
    end;
    (*---------------------*)


    (*---------------------*)
    procedure get_point;
      (* Purpose:  This procedure registers the measurement coordinates of
         one point each time it is called.
      *)
    begin
        if ( pred(num) >= num_points ) then begin
            exit; end
        else begin
            get_probe_pt(x);
            comp_point;
            write_point;

            write_prompt;
            clear_probe;
        end;
    end;
    (*---------------------*)


begin { record_points }
    erase_bottom;
    if check_filename then begin
        assign(f,filename);
        {$I-} rewrite(f); {$I+}
        if ioresult <> 0 then begin
            write('UNABLE TO OPEN ',FILENAME,'.....press enter to
      continue....');
            readln;
        end;end
```

```
else begin
    exit;
end;
erase_bottom;
move_dro(dro2);

if (charsex in ['M','m']) then begin
    write_at(36,6, 'MALE'); end
else begin
    write_at(36,6, 'FEMALE');
    end;

if replace_sn then begin
    write_at(36,1, concat('FILE:  ', original_sn) ); end
else begin
    write_at(36,1, concat('FILE:  ', filename) );
end;


write_at(36,2, 'press <s> to close file');
write_at(36,3, 'press <*> to cancel last point taken');
write_at(36,4, 'press <!> to abort point recording');
key := chr(0);
clear_probe;
line := 10;
num := 0;
c[37] := chr(13);
c[38] := chr(10);
write_prompt;

repeat
    repeat
        update_dro;
    until point_available or keypressed;
    if keypressed then begin
        read(kbd, key);
        if (key = '*') and (num > 1) then begin
            cancel_point;end
        else if key = '!' then begin
            erase_bottom;
            move_dro(dro1);
            close(f);
            erase(f);
            skip_regression := true;
            exit;
        end; end
    else BEGIN
        get_point;
        if num = 29 then begin
          delay(2000);
          erase_bottom;
          for z := 1 to 4 do begin

              case z of
```

```
                     1,2 : begin
                           gotoxy(8,9+z);
                           write('R. Tragion',hold[z]);
                           end;
                     3,4 : begin
                           gotoxy(8,11+z);
                           write('Sellion   ',hold[z]);
                           end
                  end; {case}
              end; {for z}

             gotoxy(15,18);
             write('Press  <s>  to save file');
             gotoxy(15,19);
             write('or  <!>  to abandon it.');
             delay(2000);
          end;
     END;

     until key in ['s','S'];
     close(f);

     if replace_sn then begin
          if active_file (old_sn) then begin
               assign (g, old_sn);
               erase (g);
          end;
          assign (g, original_sn);
          rename (g, old_sn);
          rename (f, original_sn);
          replace_sn := false;
     end;

     erase_bottom;
     move_dro(dro1);
end;
(*---------------------------------------------



---------------------------------------------*)
procedure runmotor;

(*
     Purpose : Temporarily changes the machine position display
               to read radius and angle instead of cartesian coordinates,
               used for troubleshooting machine problems.
*)

var
     key : char;
begin
     machine_system := true;
     move_dro(dro1);
```

```
    erase_bottom;
    write_at(5,12, 'PRESS ANY KEY TO CONTINUE');
    while keypressed do begin
        read(kbd, key);
    end;
    repeat
        update_dro
    until keypressed;
    read(kbd, key);
    machine_system := false;
end;
(*---------------------------------------------



---------------------------------------------*)
function verified : boolean;
(*
   Purpose: Reads response (from keyboard) to question about the accuracy of
   a previous input.  Sets the boolean variable "verified" true if the response
   is affirmative.
 *)
var
    c : char;
begin
    repeat
        read(kbd, c);
    until c in ['n','N','-','+','y','Y'];
    verified := c in ['y','Y','+'];
end;
(*---------------------------------------------



---------------------------------------------*)
procedure set_to_fixture;

(*
    Purpose : Procedure to calibrate the measuring machine.
    Calls erase_bottom, write_at, verified, clear_probe, point_available,
    get_probe_pt, mikedelay.
*)

var
    x : vector;
    s : string80;


    (*----------------------*)
    procedure save_to_file;
      (*
        Purpose: saves calibration data in file on station disk.  Calibration
        data file name is contained in variable "gagefile" --- presently
        gagefile := 'a:gage.prm'.
```

```
            Calls procedure mikedelay.
          *)
        var
            f : text;
        begin
            assign(f, gagefile);
            {$I-}
            rewrite(f);
            {$I+}
            if ioresult <> 0 then begin
                writeln('Unable to save calibration data.');
                mikedelay;
                close(f);
                exit;
            end;
            writeln(f,z_offset);
            writeln(f,radial_offset);
            close(f);
        end;
        (*----------------------*)

    begin { set_to_fixture }
        erase_bottom;
        write_at(2,10, 'Set axes to fixture? (y/n)');
        if verified then begin
            cbreak := true;
            clear_probe;
            erase_bottom;
            write_at(2,10, 'Take a point on the od of the fixture.');
            repeat
            until point_available;
            get_probe_pt(x);
            radial_offset := gage_dia / 2.0 + rcomp - current_radius +
              radial_offset;
            str(current_radius:9:3,s);
            write_at(2,11, concat('current radius is ',s) );
            str (radial_offset:9:3,s);
            write_at (2,12, concat('radial_offset is ',s) );

            write_at(2,10, 'take a point on the bottom of the fixture');
            clear_probe;
            repeat
            until point_available;
            get_probe_pt(x);
            z_offset := z_gage + rcomp - x[3] + z_offset;
            str(x[3]:9:3,s);
            write_at(2,11, concat('x[3] is ',s) );
            str(z_offset:9:3,s);
            write_at(2,12, concat('z_offset is ',s) );
            mikedelay;
            save_to_file;
            cbreak := false;
        end;
    end;
```

```
(*--------------------------------------------------



---------------------------------------------------*)
procedure menu (i, j : integer; s : string80);

(*
     Purpose : Writes menu item j at column i.
*)

begin
     gotoxy (i+1, top_of_bottom + 4 + j);
     write (j,'. ');
     write (s);
end;
(*--------------------------------------------------



---------------------------------------------------*)
procedure read_points;

(*
     Purpose : Reads file  a:points.text  to get the names of the
               points to be measured.
*)

var
     f : text;

     code,
     j,
     i : integer;

     s,
     sn : string80;
     f_name : string20;


     (*----------------------*)
     function check_points_txt : boolean;
     (*
        Purpose : Checks whether the file Points.txt is on the station
        disk in drive A, and whether it can be opened or not.
     *)

      BEGIN {check_points_txt}
         assign(f,namefile);          (* Namefile = POINTS.TXT, a
                                         global constant  *)
         {$I-} reset(f); {$I+}
         If ioresult <> 0 then begin
              clrscr;
              readln (kbd);
```

```
            erase_bottom;
            check_points_txt := false; end
        else begin
            check_points_txt := true;
        end;
        close(f);
    END; {Check_points_txt}
    (*----------------------*)


begin {read_points}
    fillchar(name,sizeof(name),0);
    fillchar(comp,sizeof(comp),0);
    f_name := namefile;
    if open_text_file (f, f_name) then BEGIN
        readln(f,s);  { skip first line }
        num_points := 0;
        while not eof(f) do begin
            readln(f,s);
            while s[1] = ' ' do begin
                delete(s,1,1);
            end;
            sn := copy(s,1,pos('.',s)-1);
            val(sn,i,code);
            if s = '' then begin
                exit;
            end;
            delete(s, 1, pos('.',s) );
            num_points := succ( num_points );
            name[i] := copy(s, 1, pos('  ',s) );
            delete(s,1,length(s) - pos('  ',s) );
            while s[1] = ' ' do begin
                delete(s,1,1);
            end;
            for j := 1 to 3 do begin
                if s[j] = '-' then begin
                    comp[i,j] := -1; end
                else if s[j] = '+' then begin
                    comp[i,j] := 1;
                end;
            end;
        end;
        close (f); end
    ELSE BEGIN
        clrscr;
        gotoxy (11, 13);
        writeln ('Unable to open file POINTS.TXT.');
        gotoxy(5,2);
        writeln('PRESS  <ENTER>  ONCE MORE TO GET THE  A>  PROMPT.');
        gotoxy(5,4);
        writeln('USE  "DIR A:"  TO CHECK DRIVE A: DISK FOR  POINTS.TXT.');
        gotoxy(5,6);
        writeln('COPY  POINTS.TXT  FROM ANOTHER STATION DISK IF NECESSARY.');
        gotoxy(5,8);
```

```
        writeln('THEN, TO RESTART PROGRAM FROM DOS, TYPE  "START".');
        readln(kbd);
        erase_bottom;
        halt;
    END;
end;
(*-----------------------------------------------



-----------------------------------------------*)
procedure init;

(*
    Purpose : To initialize variables when program is started;  calls
    the included procedure GET_REG, which is in file a:INITREG.PAS.
*)

var
    i,
    j : integer;

    gage_file : text;

    g_file_name : string[20];

begin  {init}
    g_file_name := 'a:gage.prm';
    file_name_made := false;
    repeat_command := false;
    replace_sn := false;

    assign(gage_file, g_file_name);
    {$i-} reset(gage_file); {$i+}
    if ioresult = 0 then begin
        close(gage_file);
        erase(gage_file);end
    else begin
        close(gage_file);
    end;
    calibrated := false;

    GET_REG;

    scxmax := 80;
    dro1 := 35;
    dro2 := 10;
    off[1] := 0;
    off[2] := 0;
    off[3] := 0;
    z_offset := 0;
    radial_offset := 0;
    machine_system := false;
    read_points;
```

```
    names[1] := 'X';
    names[2] := 'Y';
    names[3] := 'Z';
    bridge := true;
    dummy_count := 0;
    deg_to_rad := pi / 180;        {conversion factor:
                                    pi radians = 180 degrees.}
    fillchar( apreset, SIZEOF(apreset), 0);
    counts[1] := 1000.0 / 9;
    counts[2] := 50;
    counts[3] := - 50;
    for i := 1 TO 3 do begin
        for j := 1 to 3 do begin
            if i=j then begin
                final_mat[i,j] := 1.0; end
            else begin
                final_mat[i,j] := 0.0;
            end;
        end;
    end;
    before_first_point := true;
    clrscr;
    move_dro(dro1);
    snow := '00000';
end;   {init}
(*---------------------------------------------



----------------------------------------------*)
 {Include file of Pascal code a:chksubnum.pas, which  contains the procedure
 for displaying the B:SUBJECT.NUM file (from the subject disk)  on the screen.}

 {$I a:chksubnum.pas }

(*---------------------------------------------

----------------------------------------------*)
  {Include Pascal code from file A:GETSUBNO.PAS, which contains procedures for
   obtaining and verifying the subject number.}

  {$I a:getsubno.pas }
(*---------------------------------------------

----------------------------------------------*)
procedure print_file;

(*
    Purpose : Displays the available subject data files;  allows
    operator to choose one to print or return to the main menu without
    printing anything.
*)

var
```

```
s,
filename : string80;

file_count,
x,
index,
count,
i : integer;

filevar,
print : text;

rc : string80;

ex_files : array[1..3] of boolean;

num, chr_value : char;

abort_flag : boolean;


(*---------------------*)


(*---------------------*)

procedure printline;
(*
     Purpose : Adds the number and name of the point to the coordinate data
               for that point, and prints all of this information on one
          line.
*)

begin
     str(i,s);
     while length(s) < 4 do begin
          insert(' ',s,1);
     end;
     s := concat(s, '. ',name[i], ':' );
     while length(s) < 30 do begin
          insert(' ',s, length(s) + 1);
     end;
     i := succ(i);
     {$i-} writeln(lst,s,rc); {$i+}

 end;
(*---------------------*)


begin {print_file}
     file_count := 0;
     abort_flag := false;
     for index := 1 to 3 do begin
          ex_files[index] := false;
```

```
end;
i := 1;
index := 1;
erase_bottom;
gotoxy(11,11);
writeln;writeln;
writeln('Existing files : ');

filename := concat('B:SN', snow, ext);
assign(filevar, filename);
{$i-} reset(filevar); {$i+}
if ioresult = 0 then begin
     ex_files[index] := true;
     file_count := file_count + 1;
     writeln('                    ',file_count : 4, '.  ', filename);
end;
index := index + 1;
close(filevar);

filename := concat('B:OD', snow, ext);
assign(filevar, filename);
{$i-} reset(filevar); {$i+}
if ioresult = 0 then begin
     ex_files[index] := true;
     file_count := file_count + 1;
     writeln('                    ',file_count : 4, '.  ', filename);
end;
index := index + 1;
close(filevar);

filename := concat ('B:RE', snow, ext);
assign(filevar, filename);
{$i-} reset(filevar); {$i+}
if ioresult = 0 then begin
     ex_files[index] := true;
     file_count := file_count + 1;
     writeln('                    ',file_count : 4, '.  ', filename);
end;
index := index + 1;
close(filevar);

if file_count <> 0 then begin
     chr_value := chr(file_count + ord('0'));
     writeln;
     writeln;
     writeln('Enter the number of the file to be printed');
     write ('or <*> to return to menu...');
     repeat
          read(kbd, num);
     until num in ['1'..chr_value, '*'];
     writeln(num);
     if num <> '*' then begin
          writeln;
          write('Press ENTER when printer is ready......');
```

```
            readln;

            index := 0;
            count := 0;
            while count <> (ord(num) - ord('0')) do begin
                 index := index + 1;
                 if ex_files[index] = true then begin
                      count := count + 1;
                 end;
            end;
            case index of
                 1 : begin
                      filename := concat('B:SN', SNOW, EXT);
                     end;

                 2 : begin
                      filename := concat('B:OD', SNOW, EXT);
                     end;

                 3 : begin
                      filename := concat('B:RE', SNOW, EXT);
                     end;
            end; {case}

            assign (filevar, filename);
            {$i-} reset (filevar); {$i+}
            x := ioresult;

            {$i-} writeln(lst, chr(13), chr(10), 'file : ', filename, chr(13),
                         chr(10));
            {$i+}


            while (not eof(filevar)) and (not abort_flag) do begin
                 readln(filevar,rc);
                 printline;
                 rc[38] := chr(0);
            end;
            close (filevar);
       end; end
  else begin
       writeln;
       write('No files available to print....press  <enter>  to continue....');
       readln;
  end;
end;
(*-----------------------------------------------




-----------------------------------------------*)
procedure menul;
```

```
LABEL 88;

(*
    Purpose :  MAIN  DRIVER.  Displays the menu and executes the
    user's choice.
*)
LABEL 67;
const
    exit = 7;
var
    max,
    i : integer;

    s : array[1..exit] of string80;

    ch : char;

    okg : boolean;

begin
    if not calibrated then begin
        clrscr;
        set_to_fixture;
        calibrated := true;
    end;

    repeat
        retest := false;
        MOVE_DRO(DRO1);
        erase_bottom;
        s[1] := 'calibrate';          {"calibrate" replaces "set to fixture"
                                        on display menu;   s[1] still calls
                                        procedure set_to_fixture, whose name
                                        originated in an earlier version of this
                                        program in which an alternate calibration
                                        procedure was available.}
        s[2] := 'record points';
        s[3] := 'retest a subject';
        s[4] := 'print a file';
        s[5] := 'display Subject.Num file';
        s[6] := 'display machine coordinates';
        s[exit] := 'terminate program';
        max := length(s[6]) + 3;
        if not repeat_command then begin
            for i := 1 to exit do begin
                menu(scxmax div 2 - max div 2, i, s[i]);
            end;
        end;

        if repeat_command then begin
            repeat_command := false;
            ch := repeat_command_chr; end
        else begin
            repeat
```

```
            update_dro
        until keypressed;
        read(kbd, ch);
end;

If ch in ['2','3'] then BEGIN
        repeat
            begin
            get_gender(OKG);
            If not OKG then begin
                OKG := true;
                goto 67;
                end;
                                                        { Note that OKG is set
                                                          false only by procedure
                                                          get_gender, and only if
                                                          there is a problem that
                                                          needs correction on the
                                                          subject's disk. }

            end
        until gender_string in ['M','m','F','f'];
END;

if ch in ['2'..'4'] then begin
        if get_Subnol (snow) then begin
            temp_file := concat ('B:TP', snow, ext);
            original_sn := concat ('B:SN', snow, ext);
            old_sn := concat ('B:OD', snow, ext);
            retest_file := concat ('B:RE', snow, ext); end
        else begin
            ch := '0';
        end;
end;
case ch of
        '1' : set_to_fixture;

        '2' : begin
              88:writeln;
                if replace_sn then begin
                    NT := 2;
                    filename := temp_file; end
                else begin
                    NT := 1;
                    filename := original_sn;
                end;
                record_points;
                if not skip_regression then begin
                    if filename = temp_file then begin
                        filename := original_sn;
                        end;
                    regrot;
                    if remeasure then begin
                        replace_sn := true;
```

```
                        end;
                    end;
                    skip_regression := false;
                end;

            '3' : begin
                retest := true;
                filename := retest_file;
                record_points;
                end;

            '4' : print_file;

            '5' : check_BSubjectNum_file;

            '6' : runmotor;
        end;
    67:writeln;
    until ch = chr(exit + ord('0') );
end;
(*---------------------------------------------



---------------------------------------------*)
function gagefile_exists : boolean;

(*
    Purpose : Checks to see if the file containing the machine calibration
              data exists.
*)

var
    f :text;

begin
    assign(f,gagefile);
    {$I-}
    reset(f);
    {$I+}
    if ioresult = 0 then begin
        readln(f,z_offset);
        readln(f,radial_offset);
        close(f);
        gagefile_exists := true; end
    else begin
        gagefile_exists := false;
    end;
end;
(*---------------------------------------------



---------------------------------------------*)
```

```
(*
    M A I N   L I N E
*)


begin
   init;
   menu1;
   clrscr;
end.
```

```
Procedure Get_gender (var OKG : boolean);
(*
    Purpose : Reads the character variable  CHARSEX  from subject disk file
    B:subject.num.  Verifies that  charsex is in  ['M','m','F','f'].
*)

var
      ok : boolean;

      subject : text;

      ans : CHAR;

      filename : String[20];

begin {get_gender}
 REPEAT   {until ok}
   begin
       ok := false;
       OKG := TRUE;
       filename := 'B:SUBJECT.NUM';
       clrscr;
       if open_text_file(subject,filename) then begin
            readln (subject);
            readln (subject, gender_string);
            close (subject);
            if gender_string = charsex then begin
                 ok := true;
                 end
            else begin
                 beep;
                 if  (gender_string in ['M','m','F','f'])  then begin
                      gotoxy(11,7);

                      case gender_string of
                      'M','m' : write('Now measuring  MEN.');
                      'F','f' : write('Now measuring  WOMEN.')
                      end;  {case}

                      gotoxy(11,9);
                      write('OK?        (y/n)        ');
                      repeat
                           read (kbd, ans);
                      until (ans in ['Y','y','+','N','n','-']);
                      write(ans);

                      if (ans in ['Y','y','+']) then begin
                           charsex := gender_string;
                           ok := true;
                           clrscr;
                           end
                      else begin
                           OKG := FALSE;
                           gotoxy(11,11);
```

```
                        writeln('Possible error in file B:SUBJECT.NUM.
                               Return to');
                        gotoxy(11,12);
                        writeln('main menu.  Check this file
                               using option  #5.');
                        gotoxy(11,16);
                        write('Press  <enter>  to continue.....');
                        readln;
                        clrscr;
                        exit;
                    end; end
                else begin     {because gender_string is not one of [m,M,F,f]}
                    okg := false;
                    beep; beep;
                    gotoxy(11,7);
                    writeln('The gender variable is missing or unreadable
                           in file');
                    gotoxy(11,8);
                    writeln('B:SUBJECT.NUM.  Please check this file on the
                       subject"s');
                    gotoxy(11,9);
                    writeln('disk.');
                    gotoxy(11,12);
                    write('Press  <enter>  to continue.....');
                    readln;
                    exit;
                end;  end; end

       else begin      {file  B:SUBJECT.NUM  not opened properly.}
            OKG := FALSE;
            beep;
            gotoxy(11,7);
            writeln('CANNOT OPEN FILE  B:SUBJECT.NUM.');
            gotoxy(11,8);
            writeln('PLEASE CHECK SUBJECT DISK.');
            gotoxy(11,12);
            writeln('Press  <enter>  to continue.....');
            readln;
            clrscr;
            exit;
       end;
  end;
 UNTIL OK;

 case charsex of
  'M','m' :  begin
             IS := 1;
             end;
  'F','f' :  begin
             IS := 2;
             end
 end; {case}
end;  {get_gender}
```

```
Procedure get_reg;
 (* This procedure it is executed when the AHD program is started.  It
    initializes several arrays associated with the regression equations
    used to predict landmark coordinates.  It reads text file A:Reg from
    the station disk, which contains a 5-dimensional matrix of regression
    coefficients.  A:Reg is updated as better data becomes available.
 *)


{SUBPROCEDURE DECLARATIONS}
(*---------------------------------------------

---------------------------------------------*)

Procedure get_eqc;
(*
     Purpose : Procedure to read matrix EQC from the file of regression
               equation constants (coefficients).  File A:Reg is a text file,
               containing both integer and real values, read into matrix EQC
               as a series of real values.
*)

var
     eqcon  : text;

     G,H,K,L : integer;

     ok : boolean;

begin {get_eqc}
     assign (eqcon,'A:REG');
     {$I-} reset(eqcon) {$I+};
     OK := (ioresult=0);             (* OK is true if file is successfully
                                   opened.
                                      *)

     If not OK then begin
          writeln('CANNOT FIND FILE A:REG  ON STATION DISK.');end
     else begin
          for L:=1 to 2 do begin {L}
               for G:=1 to 26 do begin {G}
                    for H:=1 to 3 do begin {H}
                         for K:=1 to 8 do begin {K}
                              read(eqcon,eqc[G,H,K,L]);
                         end; {K}
                    end; {H}
                    readln(eqcon);
               end; {G}
          end; {L}
     end;

     close (eqcon);
 end; {get_eqc}
 (*---------------------------------------------
```

```
----------------------------------------------*)
procedure get_se;

(*
     Purpose : Reads array of standard error values, 'SE : 26x3x2', from the
               matrix  EQC.
*)

var
     G,H,L : integer;

begin {get_se}
     for G:=1 to 26 do begin {G}
          for H:=1 to 3 do begin {H}
               for L := 1 to 2 do begin {L}
                    SE[G,H,L] := EQC[G,H,8,L];
               end; {L}
          end; {H}
     end; {G}
end; {get_se}
(*----------------------------------------------



----------------------------------------------*)
Procedure get_ivn;


(*
     Purpose : Reads array of predictor-variable indexes,
               called 'IVN : AI283222' from matrix EQC.  IVN
               contains the predictor variables, and is itself indexed
               as follows: IVN[G,H,V,C,L] where
                          G  1..28 indicates the name of the p. Variable.
                          H  1..3  indicates the X, Y, or Z dimension.
                          V  1..2  indicates whether it is the 'A' or 'B'
                                   predictor variable.
                          C  1..2  indicates whether it is the I or J index of the
                                  A/B variable.
                          L  1..2  L=1 for male, L=2 for female.
*)

var
     G,H,L : integer;

begin {get_ivn}
     for L:=1 to 2 do begin {L}
          for G:=1 to 26 do begin {G}
               for H:=1 to 3 do begin {H}
                    (*
                      Note: The values in IVN are of type integer, so that they
```

```
                         may be used to index other arrays.  The values in EQC are
                         of type real.  Therefore it is necessary to truncate the
                         values from EQC, though they are whole numbers, so that
                         they have no decimal part (which was .0) and can be
                         treated as integers.
                       *)

                      IVN[G,H,1,1,L] := trunc(EQC[G,H,1,L]);
                      IVN[G,H,1,2,L] := trunc(EQC[G,H,2,L]);
                      IVN[G,H,2,1,L] := trunc(EQC[G,H,3,L]);
                      IVN[G,H,2,2,L] := trunc(EQC[G,H,4,L]);
                  end; {H}
              end; {G}
          end; {L}
      end; {get_ivn}

(*------------------------------------------------



------------------------------------------------*)
                                    (* main code of get_reg *)

BEGIN
   (*  Calls each of the procedures defined above.
   *)
     Get_eqc;
     Get_se;
     Get_ivn;

END;
```

```
PROCEDURE REGROT;
(*
     This procedure it receives a data array of x-, y-, and z-coordinates for
 26 facial landmarks, from which it selects the Right Tragion, Left Tragion,
 and Sellion coordinates as the basis of a "rotated" axis system. It verifies
 that those three points are in a reasonable position relative to each other,
 and rotates the array of coordinates into the new axis system. The coordinates
 are checked against themselves as follows: an estimate for each coordinate is
 calculated using the corresponding regression coefficient (from file A:REG)
 and the values of predictor landmarks from the data array itself. The
 measured value of the coordinate is then compared to the esimate. If the
 measurement falls more than 4 standard deviations from the estimate, an error
 is flagged.
*)


var    I,J,M,X : integer;


       aaer,er,est,sorterr,dpoint,rotpt : AR2832R;

       xypoints,aer,axes,
       axeserr,axer,axesest : MAT332;

       amaxer,maxer : AR2R;

       diff : AR263R;

       comment : ARS250;

{ sub-procedure declarations }

(*--------------------------------------------



---------------------------------------------*)


procedure init_rotpt;
(*
     Purpose : Initializes array ROTPT to zero before each subject's data is
rotated.
     ROTPT holds the rotated data set.
*)
var
     G, H, I : integer;

begin {init_rotpt}
     for I:=1 to 2 do begin {I}
          for G:=1 to 28 do begin {G}
               for H:=1 to 3 do begin {H}
```

```
                rotpt[G,H,I] := 0.0;
            end; {H}
        end; {G}
    end; {I}
end; {init_rotpt}
(*-----------------------------------------------


-----------------------------------------------*)
procedure init_aaer;

(*
  Purpose: Initializes array AAER to zero between subjects.
*)

var
    I, J, K : integer;

begin {init}
    for K:=1 to 2 do begin {K}
        for I:=1 to 28 do begin {I}
            for J:=1 to 3 do begin
                AAER[I,J,K]:=0.0;
            end;
        end;
    end;
end;
(*-----------------------------------------------


-----------------------------------------------*)
procedure selaxes (var pt:AR2832R;
                   var ax:MAT332);
(*
   Purpose: Selects the points which are the basis for the rotated axis system
   from the measured data set.
*)
var
    I:integer;

begin {selaxes}
    for I:=1 to 3 do begin {for I}
        AX[1,I,NT] := PT[1,I,NT];   {rt. trag.}
        AX[2,I,NT] := PT[21,I,NT];  {lt. trag.}
        AX[3,I,NT] := PT[12,I,NT];  {sellion}
    end; {for}
end; {selaxes}
(*-----------------------------------------------


-----------------------------------------------*)
```

```
Procedure exchange (var x, y: real);
(*
    Purpose : Interchanges the values of x and y.
*)

var
    temp  :  real;

begin {exchange}
    temp := x;
    x := y;
    y := temp;
end; {exchange}
(*----------------------------------------------



----------------------------------------------*)
Procedure bsort ( var AER:mat332;
                  x:integer;
                  var nt:integer);
(*
   Purpose: Sorts the values in 3x3 matrix AER into ascending order,
   in order to find the largest one.
   Calls procedure Exchange.
*)
var
    i,
    j : integer;

    inorder,
    linorder : boolean;

begin {bsort}
    for j:= 1 to 3 do begin{j}
        repeat {until inorder}
            inorder := true;  {tentatively}
            for i:=1 to x-1 do begin
                if (AER[i,j,nt] > AER[i+1,j,nt]) then begin
                    exchange (AER[i,j,nt], AER[i+1,j,nt]);
                    inorder:=false;
                end;
            end;
        until inorder
    end; {j}

    repeat {until line is in order}
        linorder:=true; {tentatively}
        for j:=1 to 2 do begin
            if (AER[3,j,nt]>AER[3,j+1,nt]) then begin
                exchange(AER[3,j,nt],AER[3,j+1,nt]);
```

```
                linorder := false
            end;
        end;{j}
    until linorder;
end;{bsort}
(*---------------------------------------------



---------------------------------------------*)
procedure bubblesort ( var ER:AR2832R;
                       NVS:integer
                       var NT:integer);
(*
   Purpose : Sorts the array ER[] into increasing order.
             After this procedure, ER[1,J,NT] contains the
             smallest, and ER[NVS,J,NT] contains the largest
             error for J and NT.
             Calls procedure exchange.
*)

var
    I,
    J : integer;

    linorder,
    inorder  :  boolean;

begin {bubblesort}
    {first sort columns.  Largest number in each column ends up in last line.}
    For J:=1 to 3 do begin  {for J}
        repeat
            inorder := true;  {tentatively}
            for I:=1 to NVS-1 do begin
                if ER[I,J,NT] > ER[I+1,J,NT] then begin {then}
                    exchange(ER[I,J,NT],ER[I+1,J,NT]);
                    inorder := false
                end; {then}
            end;
        until inorder;
    end; {for J}

    {Sort last line into smallest-to-largest order from left to right.}
    Repeat
        linorder:=true;  {tentatively}
        for J:=1 to 2 do begin {J}
            if ER[NVS,J,NT] > ER[NVS,J+1,NT] then begin {then}
                exchange(ER[NVS,J,NT],ER[NVS,J+1,NT]);
                linorder:=false;
            end; {then}
        end; {J}
    until inorder;

end; {bubblesort}
```

```
(*---------------------------------------------



---------------------------------------------*)
Procedure rotate;
 (*
      Purpose: Rotates the measured data into the new axis system.
 *)

var  axpnt : MAT332;

     backwrd,
     trnslat : MAT442;

     D,E,F,G,Z : VEC32;

     coords : VEC42;

     I1, J, K, L, subno : integer;

     H, sum : real;

     rotted : text;


     (*-----------------------*)

    Procedure norm ( var C: VEC32; var NT:integer);
     (*
        Purpose : Normalizes the 3-D vector C.
     *)
     var
          size : real;
          I : integer;

     begin  {norm}
          size := 0.0;

          For I := 1 to 3 do begin {for}
               if (abs(c[i,nt])<1e-10) then begin
                    c[i,nt] := 0.0;
               end;
               size := size + Sqr(c[i,nt]);
          end; {for}

          size := sqrt(size);

          for I := 1 to 3 do begin {for}
               c[i,nt] := c[i,nt]/size;
          end; {for}

     end; {norm}
```

```
(*-----------------------*)


(*-----------------------*)

Function dot (var A,B : VEC32; var NT:integer): real;
(*
   Purpose : Returns the scalar dot product of the two 3-dimensional
   vectors A and B.
*)
var
     T : real;

     I : integer;

begin {dot}
     T := 0.0;
     For I := 1 to 3 do begin {for}
          T := T + A[I,NT]*B[I,NT];
     end; {for}
     dot := T;
end; {dot}

(*-----------------------*)


(*-----------------------*)

Procedure cross(var a,b,c : vec32; var nt:integer);
  (*
     Purpose : Computes the cross product of the 3-dimensional vectors
     A and B, and returns the result in 3-D vector C.
  *)

begin {cross}
     C[1,NT] :=  ( (A[2,NT] * B[3,NT]) - (A[3,NT] * B[2,NT]) );
     C[2,NT] :=  ( (B[1,NT] * A[3,NT]) - (B[3,NT] * A[1,NT]) );
     C[3,NT] :=  ( (A[1,NT] * B[2,NT]) - (A[2,NT] * B[1,NT]) );
end; {cross}
(*-----------------------*)



(*-----------------------*)
Procedure matmult ( var newpnt:VEC42;
                    var matrxb:MAT442;
                    var NT:integer);
(*
   Purpose : Multiplies two matrices.
*)

var
     K,L : integer;
```

```
          spot,point1 : VEC32;
          sum : real;

     begin {matmult}
          for K:=1 to 3 do begin {for1}
               spot[K,NT] := newpnt[K,NT] + matrxb[4,K,NT];
          end; {for1}
          for K:=1 to 3 do begin {for2}
               sum := 0.0;
               for L := 1 to 3 do begin {for3}
                    sum := sum + matrxb[K,L,NT]*spot[L,NT];
               end; {for3}
               point1[K,NT] := sum;
          end; {for2}

          for K:=1 to 3 do begin {for4}
               newpnt[K,NT] := point1[K,NT];
          end; {for4}

     end; {matmult}
     (*-----------------------*)


begin {procedure rotate}

     {initialize array 'coords'}
     for I1:=1 to 4 do begin {for1}
          coords[I1,NT]:=1.0;
     end; {for1}


     { Select the points from the data file which will be the basis of
     the new axes:  Rt. Trag., Lt. Trag., and Sellion.}

     Selaxes(dpoint,axpnt);


     for I1 := 1 to 3 do begin {for I}
          D[I1,NT] := axpnt[2,I1,NT] - axpnt[1,I1,NT];
          E[I1,NT] := axpnt[3,I1,NT] - axpnt[1,I1,NT];
     end; {fori}

     norm (D,NT);

     H := dot (E,D,NT);

     for I1:=1 to 3 do begin {for I}
          G[I1,NT] := H * D[I1,NT];
          F[I1,NT] := E[I1,NT] - G[I1,NT];
     end; {for I}

     norm (F,NT);

     cross (F,D,Z,NT);
```

```
norm (Z,NT);

for I1 := 1 to 3 do begin {for I}
     trnslat[4,I1,NT] := (-axpnt[1,I1,NT]);
     trnslat[1,I1,NT] := F[I1,NT];
     trnslat[2,I1,NT] := D[I1,NT];
     trnslat[3,I1,NT] := Z[I1,NT];
end; {for I}


for J:=1 to 3 do begin  {for J}
     for K:=1 to 3 do begin  {for K1}
          coords[K,NT] := axpnt[J,K,NT];
     end; {for K1}
     matmult(coords,trnslat,nt);
     for K:= 1 to 3 do begin {for K2}
          backwrd[J,K,NT] := coords[K,NT]
     end; {for K2}
end; {for J}


coords[1,NT] := (backwrd[1,1,NT] + backwrd[2,1,NT]) / 2.0;
coords[2,NT] := backwrd[3,2,NT];
coords[3,NT] := (backwrd[1,3,NT] + backwrd[2,3,NT]) / 2.0;

{Calculate the origin in global axes and translate to anatomical axes.}
For K := 1 to 3 do begin {fork}
     sum := 0.0;
     For L := 1 to 3 do begin  {for L}
          sum := sum + (trnslat[L,K,NT] * coords[L,NT]);
     end; {for L}
     trnslat[4,K,NT] := trnslat[4,K,NT] - sum;
end; {for K}


for J:=1 to 26 do begin {for J}
     for K:=1 to 3 do begin  {for K}
          coords[K,NT] := dpoint[J,K,NT];
     end; {for K}

     matmult(coords,trnslat,nt);

     for K:=1 to 3 do begin  {for K}
          rotpt[J,K,NT] := coords[K,NT];
     end; {for K}
end; {for J}

end; {procedure rotate.}
(*-----------------------------------------------



----------------------------------------------*)
```

```
Procedure regax ( var axes,
                      axeserr,
                      axesest:MAT332);
 (*
    Purpose : Uses the regression equations in eqc to check the 3 landmarks
              which form the axes for the rotation.
              Calls no other procedures.
 *)

var
    g, h : integer;

begin {regax}
    for h:=1 to 3 do begin {h}

        { Estimate Rt.Trag.}
        axesest[1,h,nt] := (  dpoint[ ivn[1,h,1,2,is], ivn[1,h,1,1,is], nt ]
                                                       * eqc[1,h,5,is]  )
                         + (  dpoint[ ivn[1,h,2,2,is], ivn[1,h,2,1,is], nt ]
                                                       * eqc[1,h,6,is]  )
                         +  eqc[1,h,7,is];

        { Estimate Lt. Trag.}
        axesest[2,h,nt] := (  dpoint[ ivn[21,h,1,2,is], ivn[21,h,1,1,is], nt ]
                                                       * eqc[21,h,5,is]  )
                         + (  dpoint[ ivn[21,h,2,2,is], ivn[21,h,2,1,is], nt ]
                                                       * eqc[21,h,6,is]  )
                         + eqc[21,h,7,is];

        { Estimate Sellion }
        axesest[3,h,nt] := (  dpoint[ ivn[12,h,1,2,is], ivn[12,h,1,1,is], nt ]
                                                       * eqc[12,h,5,is]  )
                         + (  dpoint[ ivn[12,h,2,2,is], ivn[12,h,2,1,is], nt ]
                                                       * eqc[12,h,6,is]  )
                         + eqc[12,h,7,is];

    end; {h}

    { Find the differences between estimated and measured data, divided by the
 standard errors.}
    For h:=1 to 3 do begin {h}
        axeserr[1,h,nt] := (axes[1,h,nt] - axesest[1,h,nt]) / se[1,h,is];
        axeserr[2,h,nt] := (axes[2,h,nt] - axesest[2,h,nt]) / se[21,h,is];
        axeserr[3,h,nt] := (axes[3,h,nt] - axesest[3,h,nt]) / se[12,h,is];

        for g:=1 to 3 do begin {g}
            if axeserr[g,h,nt] < 0.0 Then begin
                axeserr[g,h,nt]:=(-axeserr[g,h,nt]);
            end;
        end;{g}
    end;{h}
end;{regax}
(*-------------------------------------------
```

```
---------------------------------------------*)
procedure regeq;

(*
    Purpose : Estimates each data point and compares the estimated and measured
   values.
    It calls no other procedures.
*)

var
    g, h,
    index1i, index1j,
    index2i, index2j : integer;

begin {regeq}

    { regression estimate }
    for g:=1 to NVS do begin  {for g}
         for h:=1 to 3 do begin  {for h}
              index1i := ivn[g,h,1,1,is];    index1j := ivn[g,h,1,2,is];
              index2i := ivn[g,h,2,1,is];    index2j := ivn[g,h,2,2,is];

              est[g,h,nt] := (rotpt[index1j,index1i,nt] * eqc[g,h,5,is])
                             + (rotpt[index2j,index2i,nt] * eqc[g,h,6,is])
                             + eqc[g,h,7,is];

              {  Calculate the error for each landmark's coordinates, as the
              difference between estimated and measured data, divided by the
              standard error of estimate. }

              er[g,h,nt] := (rotpt[g,h,nt] - est[g,h,nt]) / se[g,h,is];

                 { Note:  The following 4  "writeln" commands appear to do
                  nothing except write a blank line to the screen;  however,
                  they also caused this segment of the program to run
                  properly when they were inserted. }

              If g=1 then begin
                   er[g,h,nt]:=axeserr[1,h,nt];
              end;
              writeln;
              If g=21 then begin
                   er[g,h,nt]:=axeserr[2,h,nt];
              end;
              writeln;
              If g=12 then begin
                   er[g,h,nt]:=axeserr[3,h,nt];
              end;
              writeln;
              If er[g,h,nt] < 0.0 Then begin
                   er[g,h,nt]:=(-er[g,h,nt]);
              end;
```

```
                writeln;

            end; {for h}
        end; {for g}
end; {regeq}
(*-----------------------------------------------



-----------------------------------------------*)
Procedure read_measurement_file;
(*
        Purpose : Reads the measurement data from subject's data file,  the filename
        starting with  SN, OD, or RE.
        Calls no other procedures.
*)

Var
        filevar : text;

        i : integer;

        OK : boolean;

begin {read_measurement_file}

        gotoxy(15,15);


        assign(filevar, filename);

        {$I-}reset(filevar){$I+};
        OK := (IOresult = 0);
        If not OK then  begin
                writeln('CANNOT FIND FILE ',FILENAME,' TO DO REGRESSION ANALYSIS.');
                readln;
                end
        else begin
                for i:= 1 to 28 do begin {for i}
                        readln(filevar,dpoint[i,1,nt],dpoint[i,2,nt],dpoint[i,3,nt]);
                end; {for i}
        end;
        close(filevar);
end; {read_measurements}
(*-----------------------------------------------



-----------------------------------------------*)
procedure ddfault;

(*
        Purpose : Checks the data file for non-measured points,
                  and replaces these values with (999.0,999.0,999.0).
```

```
*)

Var
     i,j : integer;

begin {ddfault}
     for i:= 1 to 28 do begin {fori}
          If ((dpoint[i,1,nt] < 80.0)
                            And (dpoint[i,2,nt] < -190.0)
                            And (dpoint[i,3,nt] < 25.0)) then begin {then}
               for j:=1 to 3 do begin
                    dpoint[i,j,nt] := 999.0;
               end;
          end; {then}
     end; {for i}
end; {ddfault}
(*----------------------------------------------



----------------------------------------------*)
procedure check_errors;

var
     i, j : integer;

begin {check}
     for i:=1 to NVS do begin {i}
          for j:=1 to 3 do begin
               sorterr[i,j,nt] := er[i,j,nt];
          end;
     end; {i}
     bubblesort(sorterr,nvs,nt);
     maxer[nt] := sorterr[nvs,3,nt];
     writeln;
end; {check}
(*----------------------------------------------


----------------------------------------------*)

procedure writeval;


     (*-----------------------------------*)
     procedure write_error_sub ( nt:integer );

     (*
          Purpose : Copies error file to subject's disk.
     *)


     var
          i : integer;
```

```
     nts : Sl;

     error : text;

begin
     str(nt,nts);
     assign(error,concat('B:ERROR',NTS,'.7'));
     rewrite(error);

     writeln(error,snow,nt:6);

     for i:=1 to nvs do begin  {for i}
          writeln (error, er[i,1,nt]:12:4, er[i,2,nt]:12:4, er[i,3,nt]:12:4);

     end; {for i}
     writeln(error, 'Largest error is ', maxer[nt]:7:4);
     close(error);
end; {write}
(*---------------------------------------------



---------------------------------------------*)

procedure write_rot_sub (nt : integer);
(*
     Purpose : Writes rotated data to subject's disk.  File rotdat.7
*)

var
     rotdata : text;

     I : integer;

     nts : sl;

begin {write}
     str (nt,nts);
     assign ( rotdata, concaT('B:ROTDAT', nts, '.7'));
     rewrite (rotdata);
     writeln ( rotdata, 'rotated data');
     writeln ( rotdata, subno:5,is:2,nt:6, nt:3, amaxer[nt]:12:4,
   maxer[nt]:12:4);
     for i:=1 to nvs do begin {for i}
          writeln ( rotdata, rotpt[i,1,nt]:12:4, rotpt[i,2,nt]:12:4,
      rotpt[i,3,nt]:12:4);
     end; {for i}
     close(rotdata);
end; {write}
(*---------------------------------------------
```

```
---------------------------------------------*)

(*
              C O M M E N T

    Procedures  FIND_DIFF  and  ASK_EX  are used by  the 4 procedures
immediately below them: FIRST_GOOD, FIRST_BAD, etc.


*)
(*---------------------------------------------



---------------------------------------------*)
procedure find_diff;

(*
    Purpose : Create matrix of differences between first and second sets of
   rotated  data.
*)

var
    diff : ar263r;

    g, h, i, j : integer;

    differ : text;

begin {find_diff}
     {determine differences.}
     For g:=1 to 26 do begin {g}
          for h:=1 to 3 do begin {h}
               diff[g,h] := rotpt[g,h,2] - rotpt[g,h,1];
          end;{h}
     end;{g}

     { Write matrix on subject's disk. }
     assign ( differ, 'B:DIFMATR');
     rewrite ( differ);
     writeln ( differ,'Matrix of differences between first and second rotated
files.');
     Writeln ( differ,subno:5);
     for I := 1 to 26 do begin {i}
          writeln( differ, diff[i,1]:12:3, diff[i,2]:12:3, diff[i,3]:12:3);
     end; {for i}
     close(differ);
end; {find_diff}
(*---------------------------------------------



---------------------------------------------*)
procedure ask_ex;
```

```
label 15,34;

var
     i, j : integer;

     cmt : text;

     ans : char;

     ext : s1;

     fname : s11;

begin {ask_ex}
     str(nt,ext);
     fname := concat('B:COMMENT.',ext);

     If  not((nt=2) and (maxer[nt] > ck))  then begin {then 1}
          15:write('WOULD YOU LIKE TO MAKE A COMMENT?           (Y/N)    ');

          read(kbd,ans);
          writeln(ans);
          case ANS of
               'Y','y','+' : begin
                    writeln('PLEASE WRITE YOUR COMMENT.   (3 LINES)');
               end;

               'N','n','-' : begin

                    goto 34;
               end;

               else begin
                    goto 15
               end;
          end;
     end;

     If  ((nt=2) and (maxer[nt] > ck)) then begin {then}
          gotoxy(5,13);
          writeln('BOTH MEASUREMENTS HAVE PRODUCED ONE OR MORE POINTS OUTSIDE
                    THE EXPECTED ');
          writeln('RANGE.  PLEASE WRITE ANY COMMENTS OR OBSERVATIONS WHICH
COULD HELP EXPLAIN');
          writeln('THIS.  (3 LINES)');
     end; {then}

     for I := 1 to 3 do begin
          readln(comment[i]);
     end;
     writeln('THANKS.');
     write('Please wait....');
```

```
    if  ((nt=2) and (maxer[nt] > ck)) then begin
         gotoxy(5,21);
         write('Getting ready for the next subject....');
    end;

    {write to subject's disk}
    assign(cmt,fname);
    rewrite(cmt);
    writeln(cmt, snow,'   ',nt:1);
    for j:=1 to 3 do begin
         writeln(cmt,comment[j]);
    end;
    close(cmt);
34:end; {ask_ex}
(*---------------------------------------------



----------------------------------------------*)
procedure first_good;

begin {first_good}
     sound(450); delay(350); nosound;
     clrscr;
     writeln('FIRST MEASUREMENTS ARE GOOD...');

     write_error_sub(nt);

     write_rot_sub(nt);

     remeasure := false;

end; {first_good}
(*---------------------------------------------



----------------------------------------------*)
procedure first_bad;

begin {procedure}

     sound(650); delay(500); nosound;
     remeasure := true;
     clrscr;
     writeln('ONE OR MORE POINTS IS OUT OF THE EXPECTED RANGE.');
     ask_ex;
     writeln;
     writeln('PLEASE REMEASURE SUBJECT ',snow,'.');
     Writeln;
     write('Please wait.....');
     writeln;

     write_rot_sub(nt);
```

```
        write_error_sub(nt);

        write('PRESS  <ENTER>  TO CONTINUE......');
        readln;

    end; {procedure}
    (*--------------------------------------------



    --------------------------------------------*)
    procedure second_good;
    begin {2nd good}
        sound(450); delay(350); nosound;
        clrscr;
        writeln('SECOND MEASUREMENT IS GOOD...');
        find_diff;
        write_rot_sub(nt);
        write_error_sub(nt);
        remeasure := false;
    end; {2nd good}
    (*--------------------------------------------



    --------------------------------------------*)
    procedure two_bad;

    var
        tempnt : integer;

    begin {two_bad}
        sound(700); delay(500); nosound;
        ask_ex;
        for tempnt := 1 to 2 do begin {tempnt}
            write_error_sub(tempnt);
            write_rot_sub(tempnt);
        end; {tempnt}
        find_diff;
        remeasure := false;
    end; {two_bad}

(*------------------------------------------------*)

                (* Main Line of Writeval *)
begin
    { Evaluate status of data file. }

    if ((NT=1) and (maxer[NT]<CK)) then begin
        first_good;
    end;


    if ((NT=1) and (maxer[NT]>CK)) then  begin
```

```
        first_bad;
    end;

    if ((NT=2) and (maxer[NT]<CK)) then begin
        second_good;
    end;

    if ((NT=2) and (maxer[NT]>CK)) then begin
        two_bad;
    end;

end;   (* writeval *)




(*---------------------------------------------


---------------------------------------------*)

BEGIN  {MAINCODE}                           (* M A I N   L I N E *)



    init_rotpt;

    init_aaer;

    {initialize flags}
    maxer[NT] :=0.0;
    amaxer[NT] := 0.0;

    read_measurement_file;

    ddfault;

    selaxes(dpoint,xypoints);

    regax(xypoints,axeserr,axesest);      {REGEQ on the 3 unrotated axis points,
                                           giving the estimates and errors for
                                           those  3.}


      { Copy AXESERR into AXER so that AXER can be sorted to find the largest
        error. }

    for I:=1 to 3 do begin {I}
        for J:=1 to 3 do begin {J}
            axer[I,J,NT] := axeserr[I,J,NT];
        end; {J}
    end; {I}
```

```
     bsort(axer,3,NT);            {Sort the 9 errors}

     amaxer[NT] := axer[3,3,NT];  {The largest of the 9 errors will be in
axer[3,3,NT].
                                   Set AMAXER.}

     rotate;                      {creates array ROTPT  which contains the rotated

                                   data from DPOINT}

     regeq;                       {test whole rotated file.}


     check_errors;

     writeval;
end;
```

```
Procedure Check_BSubjectNum_file;

(*
   Purpose : Displays the file  B:Subject.num, containing the subject number,
             gender, etc., from the subject's disk.  This information cannot
             be altered, only displayed.
             Calls function open_text_file from main program.
*)
var
     filename, line : string[20];
     filevar : text;
     L : integer;

begin
     clrscr;
     filename := 'B:subject.num';
     gotoxy(11,4);
     if open_text_file (filevar,filename) then begin

          for L := 1 to 2 do begin
               readln (filevar,line);
               gotoxy(11,4+L);
               writeln (line);
          end;
          close (filevar);
          end

     else begin
          writeln('Cannot open file ',filename);
          gotoxy(11,5);
          writeln('Check subject"s disk.');
     end;

     gotoxy(11,14);
     write ('Press  <enter>  to continue.....');
     readln;
end;
```

```
function get_SUBNO1 (var snow : s5) : boolean;

(*
    Purpose : Allows user to input a subject number from the keyboard, which
    will then be used to generate a filename.
*)

var

    i : integer;

    ok : boolean;

    subject : text;

    subn_str,
    dsk_subn_str : string80;

    ans : char;

    filename : string20;


    (*---------------------*)
    procedure delete_spaces (var s : string80);
      (*
        Purpose: Deletes leading spaces from the subject number entered
        by the operator or found on the subject disk; because all leading
        spaces are deleted, the program can read the number from anywhere
        on the line.
      *)

    begin
        if length (s) > 0 then begin
            repeat
                if s [1] = ' ' then begin
                    delete (s, 1, 1);
                end;
            until (s = '') or (s [1] <> ' ');
        end;
    end;
    (*---------------------*)


    (*---------------------*)
    procedure pad_with_zeroes (count : integer;
                               var s : string80);
      (* Purpose : Pads subject numbers of 4 or fewer digits with leading zeros,
         because the data file name uses a 5-digit subject number.
      *)
    begin
        while length (s) < count do begin
            insert ('0', s, 1);
        end;
```

```
    end;
    (*---------------------*)


    (*---------------------*)
    function numerical (var s : string80) : boolean;
     (*  Purpose : Verifies that the characters entered for the subject
         number are numeric, and rejects those characters that aren't.
         Depends on the contiguous positions of the characters '0','1',
         '2',...'9'  on the ASCII table.
      *)

    var
         i : integer;
    begin
         numerical := true;
         if length (s) > 0 then begin
              for i := 1 to length (s) do begin
                   if (s [i] < '0') or (s [i] > '9') then begin
                        numerical := false;
                   end;
              end; end
         else begin
              numerical := false;
         end;
    end;
    (*---------------------*)



begin {get_SUBNO}
     ok := false;
     get_subnol := true;

     (*
        Read subject number from subject disk.
     *)

     filename := 'b:subject.num';
     if open_text_file (subject, filename) then begin
          readln (subject, dsk_subn_str);
          delete_spaces (dsk_subn_str);
          if numerical (dsk_subn_str) then begin
               pad_with_zeroes (5, dsk_subn_str);

                    (*     Variable 'snow' contains the previous subject number,
                           (the subject number used for the last operation).

                           Variable  'dsk_subn_str' contains the number on the
                           disk currently in drive B:, which will (if verified)
                           be used for the procedure at hand.

                           If the two numbers are the same, there is no need to
```

```
                    verify the 'new' number by asking the operator to
                    type it, because the procedure calling 'get_SUBNO' is
                    simply another operation with the same subject.

                    If the two numbers are different, the disk has been
                    changed since the last operation. The program asks the
                    operator for the new subject number in order to ensure
                    that the subject number on the disk is the indeed the
                    subject number of the person being measured.
               *)
            if snow = dsk_subn_str then begin
                ok := true;
            end;
        end;
    end;
    close (subject);

    (*
        If the "new" subject number from the disk, and "previous" subject number
        from memory are different, "ok" is false. Ask the operator to type in
        the new or correct number.
    *)
    if not ok then begin
        repeat
                (* Repeat the rest of this procedure until "ok" is true;
                   that is, until the disk subject number and the
                   operator-entered subject number are the same.
                   "Ok" is initially set true, but during the procedure
                   it may be set false, so that the procedure is repeated.
                   The following conditions cause ok=false:
                          * Operator wants to re-enter the number;
                          * File b:subject.num cannot be opened, or does not
                                contain a recognizable subject number;
                          * Subject number entered does not match the one on
                                the subject's disk.
                *)

            repeat
                    (* Repeat until the operator has successfully entered a
                       subject number. "Ok" is initially set true, but will
                       be set false if the operator wants to re-enter the
                       number.
                    *)
                ok := true;
                erase_bottom;

                if retest then begin       (* Notify operator that the next
                                              data recorded will be treated
                                              as retest data.
                                           *)
                    gotoxy (11, 10);
                    write ('RETEST');
                end;
```

```
          gotoxy (11, 11);
          write ('Enter subject number :  ');
          get_int_str (5, subn_str);            (*  Read subject number
                                                    from screen.
                                                    Echo subject number
                                                    back to screen.
                                                *)
          gotoxy (11, 13);
          writeln ('Subject number ', subn_str, '.');
                                                (*  Ask operator to
                                                    verify number.
                                                *)
          gotoxy (11, 14);
          write ('OK  (y/n) ? ');
          repeat
               read (kbd, ans);
          until ans in ['y', 'Y', '+', 'n', 'N','-'];
          write (ans);                           (*  Echo 'y' or 'n' to
                                                    screen.
                                                 *)
          if ans in ['n', 'N','-'] then begin    (*  Subject no. was
                                                 probably mis-typed.
                                                     Set ok=false so
                                                     that verification
                                                     steps are repeated.
                                                 *)
               ok := false;
               erase_bottom;end

          else begin
               pad_with_zeroes (5, subn_str);
          end;
     until ok;                                   (* until subject number
                                                    is successfully
                                                entered
                                                  *)

     (* Compare the subject number entered (SUBNO1) to
        the subject number on the subject's disk (SUBNO).
     *)

     filename := 'b:subject.num';
     if open_text_file (subject, filename) then begin
                                            (* Open_text_file =
                                           true means that file
                                                    b:subject.num can be
                                                    opened.
                                                 *)
          readln (subject, dsk_subn_str);
delete_spaces (dsk_subn_str);
          if numerical (dsk_subn_str) then begin
                                                 (* Function "numerical"
                                                    is true if only
                                                    numeric characters
```

```
                                        are found on line 1
                                        in b:subject.num.
                                      *)
    pad_with_zeroes (5, dsk_subn_str);


      (* If the number entered at the keyboard matches the
         number on the subject's disk, this number will be
         used.
      *)
    if subn_str = dsk_subn_str then begin
         snow := subn_str; end

      (* This branch is executed only if the number entered
         at the keyboard does not match the number on the
         subject's disk.  One or both numbers is wrong.  Asks
         the operator to straighten things out.
      *)
    else begin
         gotoxy (11, 18);
         writeln ('***  ATTENTION  ***   The subject number
                  on disk in drive B: is ',dsk_subn_str,'.');
         gotoxy (11, 20);
         writeln ('The number entered is ', subn_str);
         gotoxy (11, 22);
         writeln ('Change disk in drive B: if necessary');
         gotoxy (11, 23);
         write ('Press any key to re-enter subject
                number...');
         beep;
         key2Continue;
         ok := false;
    end;end


  (*  This branch is executed only if function "numerical" is
      false, when non-numeric characters are found in the
      subject number field in file b:subject.num.
  *)
  else begin
      ok :=false;
      gotoxy (1, 16);
      writeln ('***  ATTENTION  ***     Illegal subject number
              <', dsk_subn_str,'> in file B:SUBJECT.NUM.');
      writeln ('                            Check for mis-typed
               subject number in file SUBJECT.NUM');
      writeln ('                            or faulty diskette. ');

      gotoxy (1, 21);
      write ('Press any key to return to menu...');
      beep;
      key2Continue;
      ok := true;
      get_subnol := false;
```

```
                end; end

            (*  This branch is executed only if file b:subject.num on the
                subject's disk cannot be opened.
            *)
            else begin
                gotoxy (11, 18);
                writeln ('***  ATTENTION  ***       Cannot find file
                        B:SUBJECT.NUM, containing');
                gotoxy (11, 19);
                writeln ('the subject"s number on subject"s disk.  Verify that
                        subject disk is in ');
                gotoxy (11, 20);
                writeln ('drive <B> and subject disk contains the file
                  <SUBJECT.NUM>');
                gotoxy (11, 22);
                write ('Press any key to continue....');
                key2Continue;
                ok := false;
            end;
            close (subject);
        until ok;
        (* The current subject number is now the number on the subject's disk,
           which has been verified by the operator.
        *)
    end;
END; {get_SUBNO}
```

# APPENDIX F.

Validation Test Data

## APPENDIX F.

Validation Test Data

The following group of tables provide the complete set of data obtained from validation studies of the AHD. The method and procedures used are described in the body of the report. In general, the results are given as simple means for the "n" of subjects or tests involved. Absolute values are used in all tables. Although some error is incurred in the calculation of grand means (means of means), the technique is used here in some cases to indicate general trends for the numerous variables involved.

In some tables observer error is presented as the differences in value in each axis separately (F-1, F-2, F-5, F-10, F-11, F-12). In other tables, the observer error is the distance, in 3-D space, between the first and subsequent attempts at locating a given point (F-3, F-4, F-7, F-8, F-9). In tables where breadths are compared, the observer error is the difference between the two measurements of breadth (F-6, F-13).

TABLE F-1. Intraobserver Error for Each Axis of the Wooden Headform Measured in the AHD: Trial 1 vs. Trial 2 for Four Operators (values in millimeters).

| No. | Landmark Name | X AXIS Range | X AXIS Mean | Y AXIS Range | Y AXIS Mean | Z AXIS Range | Z AXIS Mean |
|---|---|---|---|---|---|---|---|
| 1. | R Tragion | 0.0 - 0.3 | 0.2 | 0.1 - 0.2 | 0.1 | 0.1 - 0.6 | 0.4 |
| 2. | R Infraorbitale | 0.0 - 0.2 | 0.1 | 0.0 - 0.9 | 0.6 | 0.1 - 1.2 | 0.6 |
| 3. | R Alare | 0.0 - 0.3 | 0.1 | 0.0 - 0.1 | 0.0 | 0.0 - 0.7 | 0.3 |
| 4. | R Cheilion | 0.1 - 0.4 | 0.2 | 0.1 - 0.8 | 0.3 | 0.0 - 0.4 | 0.2 |
| 5. | R Gonion | 0.1 - 0.8 | 0.4 | 0.1 - 0.4 | 0.2 | 0.0 - 0.8 | 0.4 |
| 6. | R Zygion | 0.1 - 0.4 | 0.2 | 0.1 - 0.2 | 0.1 | 0.2 - 1.2 | 0.7 |
| 7. | R Ectoorbitale | 0.1 - 1.2 | 0.5 | 0.1 - 1.0 | 0.4 | 0.0 - 0.5 | 0.2 |
| 8. | R Zygofrontale | 0.0 - 0.4 | 0.2 | 0.0 - 0.3 | 0.2 | 0.4 - 0.6 | 0.5 |
| 9. | R Frontotemporale | 0.0 - 0.4 | 0.2 | 0.0 - 0.2 | 0.2 | 0.3 - 0.6 | 0.5 |
| 10. | Crinion | 0.1 - 0.2 | 0.1 | 0.1 - 0.4 | 0.2 | 0.0 - 0.7 | 0.3 |
| 11. | Glabella | 0.0 - 0.1 | 0.1 | 0.1 - 0.5 | 0.2 | 0.4 - 0.9 | 0.5 |
| 12. | Sellion | 0.0 - 0.1 | 0.1 | 0.1 - 0.6 | 0.3 | 0.4 - 1.1 | 0.7 |
| 13. | Pronasale | 0.0 - 0.1 | 0.1 | 0.1 - 0.2 | 0.1 | 0.3 - 0.9 | 0.7 |
| 14. | Subnasale | 0.1 - 0.3 | 0.2 | 0.1 - 0.7 | 0.3 | 0.2 - 0.3 | 0.3 |
| 15. | Stomion | 0.1 - 0.8 | 0.3 | 0.1 - 0.6 | 0.3 | 0.1 - 0.9 | 0.5 |
| 16. | Promenton | 0.0 - 0.2 | 0.1 | 0.1 - 0.3 | 0.3 | 0.0 - 0.4 | 0.1 |
| 17. | Menton | 0.0 - 0.9 | 0.3 | 0.0 - 1.3 | 0.5 | 0.0 - 0.6 | 0.3 |
| 18. | L Cheilion | 0.0 - 0.5 | 0.3 | 0.1 - 0.9 | 0.3 | 0.2 - 2.0 | 0.9 |
| 19. | L Alare | 0.5 - 1.5 | 0.8 | 0.1 - 0.3 | 0.2 | 0.2 - 0.6 | 0.4 |
| 20. | L Gonion | 0.0 - 0.9 | 0.4 | 0.0 - 0.3 | 0.2 | 0.0 - 0.8 | 0.5 |
| 21. | L Tragion | 0.1 - 0.3 | 0.2 | 0.1 - 0.5 | 0.3 | 0.1 - 0.7 | 0.4 |

TABLE F-1. Continued

| No. | Landmark Name | X AXIS Range | X AXIS Mean | Y AXIS Range | Y AXIS Mean | Z AXIS Range | Z AXIS Mean |
|---|---|---|---|---|---|---|---|
| 22. | L Zygion | 0.1 - 0.5 | 0.3 | 0.0 - 0.1 | 0.0 | 0.3 - 0.5 | 0.4 |
| 23. | L Infraorbitale | 0.0 - 0.1 | 0.0 | 0.0 - 0.5 | 0.2 | 0.0 - 0.5 | 0.2 |
| 24. | L Ectoorbitale | 0.1 - 0.3 | 0.2 | 0.0 - 0.3 | 0.2 | 0.1 - 0.5 | 0.4 |
| 25. | L Zygofrontale | 0.0 - 0.5 | 0.2 | 0.1 - 0.2 | 0.1 | 0.1 - 1.5 | 0.6 |
| 26. | L Frontotemporale | 0.0 - 0.4 | 0.3 | 0.2 - 0.3 | 0.3 | 0.1 - 1.1 | 0.6 |
| 27. | Sellion | 0.0 - 0.1 | 0.1 | 0.1 - 0.3 | 0.2 | 0.1 - 0.4 | 0.3 |
| 28. | R Tragion | 0.1 - 0.6 | 0.3 | 0.0 - 1.1 | 0.4 | 0.1 - 1.1 | 0.4 |
| | GRAND MEAN | 0.06-0.46 | 0.23 | 0.07-0.48 | 0.24 | 0.14-0.79 | 0.44 |

TABLE F-2. Interobserver Error for Each Axis of the Wooden Headform Measured in the AHD: Observer #1 vs. Observer #2, Observer #3 vs. Observer #4 - Two Trials per Pair (values in millimeters).

| | | X AXIS | | Y AXIS | | Z AXIS | |
|---|---|---|---|---|---|---|---|
| No. | Landmark Name | Range | Mean | Range | Mean | Range | Mean |
| 1. | R Tragion | 0.2 - 0.6 | 0.4 | 0.0 - 0.1 | 0.0 | 0.1 - 0.4 | 0.2 |
| 2. | R Infraorbitale | 0.0 - 0.2 | 0.1 | 0.1 - 1.0 | 0.6 | 0.1 - 1.1 | 0.6 |
| 3. | R Alare | 0.1 - 0.7 | 0.4 | 0.0 - 0.1 | 0.1 | 0.0 - 1.4 | 0.8 |
| 4. | R Cheilion | 0.0 - 0.5 | 0.2 | 0.2 - 0.4 | 0.3 | 0.0 - 0.6 | 0.4 |
| 5. | R Gonion | 0.0 - 0.8 | 0.3 | 0.0 - 0.2 | 0.1 | 0.0 - 0.7 | 0.4 |
| 6. | R Zygion | 0.0 - 0.5 | 0.3 | 0.1 - 0.2 | 0.1 | 0.2 - 1.1 | 0.8 |
| 7. | R Ectoorbitale | 0.0 - 1.1 | 0.5 | 0.0 - 0.8 | 0.3 | 0.0 - 1.0 | 0.4 |
| 8. | R Zygofrontale | 0.0 - 0.3 | 0.2 | (0.1) | 0.1 | 0.2 - 0.7 | 0.4 |
| 9. | R Frontotemporale | 0.1 - 0.2 | 0.1 | 0.1 - 0.3 | 0.2 | 0.3 - 0.4 | 0.4 |
| 10. | Crinion | (0.1) | 0.1 | 0.1 - 0.4 | 0.2 | 0.2 - 0.6 | 0.4 |
| 11. | Glabella | 0.0 - 0.2 | 0.1 | 0.2 - 0.5 | 0.3 | 0.3 - 0.9 | 0.5 |
| 12. | Sellion | 0.0 - 0.1 | 0.1 | 0.1 - 0.6 | 0.3 | 0.4 - 1.1 | 0.7 |
| 13. | Pronasale | 0.0 - 0.1 | 0.1 | 0.1 - 0.5 | 0.3 | 0.0 - 1.0 | 0.3 |
| 14. | Subnasale | 0.0 - 1.5 | 0.7 | 0.0 - 1.0 | 0.3 | 1.5 - 2.6* | 2.1* |
| 15. | Stomion | 0.1 - 1.1 | 0.4 | 0.5 - 1.5 | 0.8 | 0.1 - 1.1 | 0.6 |
| 16. | Promenton | 0.0 - 0.3 | 0.2 | 0.1 - 0.2 | 0.2 | 0.1 - 1.0 | 0.5 |
| 17. | Menton | 0.4 - 2.6 | 1.2 | 0.3 - 0.8 | 0.6 | 0.1 - 1.3 | 0.6 |
| 18. | L Cheilion | 0.0 - 0.3 | 0.2 | 0.1 - 0.9 | 0.3 | 0.2 - 1.5 | 0.7 |
| 19. | L Alare | 0.1 - 2.1 | 0.7 | 0.0 - 0.4 | 0.2 | 0.1 - 0.3 | 0.2 |
| 20. | L Gonion | 0.1 - 0.4 | 0.3 | 0.1 - 0.4 | 0.2 | 0.2 - 0.8 | 0.5 |
| 21. | L Tragion | 0.2 - 0.4 | 0.3 | 0.1 - 0.8 | 0.4 | 0.1 - 1.1 | 0.5 |

* Values reflect difference in measurement procedures used by operators.

TABLE F-2. Continued

| No. | Landmark Name | X AXIS Range | X AXIS Mean | Y AXIS Range | Y AXIS Mean | Z AXIS Range | Z AXIS Mean |
|---|---|---|---|---|---|---|---|
| 22. | L Zygion | 0.0 - 0.6 | 0.2 | 0.0 - 0.1 | 0.0 | 0.6 - 0.8 | 0.7 |
| 23. | L Infraorbitale | 0.0 - 0.1 | 0.0 | 0.0 - 0.4 | 0.2 | 0.0 - 0.5 | 0.2 |
| 24. | L Ectoorbitale | 0.2 - 0.8 | 0.4 | 0.1 - 0.6 | 0.3 | 0.3 - 0.8 | 0.5 |
| 25. | L Zygofrontale | 0.0 - 0.3 | 0.2 | 0.0 - 0.2 | 0.1 | 0.0 - 0.7 | 0.4 |
| 26. | L Frontotemporale | 0.1 - 0.3 | 0.2 | 0.0 - 0.4 | 0.2 | 0.3 - 1.0 | 0.6 |
| 27. | Sellion | 0.0 - 0.1 | 0.0 | 0.1 - 0.4 | 0.2 | 0.1 - 0.9 | 0.5 |
| 28. | R Tragion | 0.0 - 0.5 | 0.3 | 0.1 - 0.4 | 0.2 | 0.0 - 0.6 | 0.3 |
| | GRAND MEANS | 0.06-0.60 | 0.29 | 0.09-0.49 | 0.25 | 0.20-0.93 | 0.54 |

TABLE F-3. Intraobserver Error for the Wooden Headform Measured in the AHD (3-D distance values in millimeters; points not rotated).

Trial #1 vs. Trial #2

| No. | Landmark Name | Observer #1 | Observer #2 | Observer #3 | Observer #4 | Grand Mean |
|---|---|---|---|---|---|---|
| 1. | R Tragion | 0.4 | 0.6 | 0.4 | 0.6 | 0.5 |
| 2. | R Infraorbitale | 0.1 | 1.5 | 0.9 | 0.9 | 0.8 |
| 3. | R Alare | 0.4 | 0.1 | 0.1 | 0.7 | 0.3 |
| 4. | R Cheilion | 0.3 | 1.0 | 0.3 | 0.4 | 0.5 |
| 5. | R Gonion | 0.5 | 0.4 | 0.8 | 0.9 | 0.7 |
| 6. | R Zygion | 0.7 | 0.5 | 0.6 | 1.1 | 0.7 |
| 7. | R Ectoorbitale | 0.4 | 1.6 | 0.6 | 0.3 | 0.7 |
| 8. | R Zygofrontale | 0.4 | 0.7 | 0.5 | 0.6 | 0.6 |
| 9. | R Frontotemporale | 0.7 | 0.7 | 0.4 | 0.4 | 0.6 |
| 10. | Crinion | 0.3 | 0.4 | 0.3 | 0.7 | 0.4 |
| 11. | Glabella | 0.4 | 0.6 | 0.5 | 0.9 | 0.6 |
| 12. | Sellion | 0.4 | 1.1 | 0.4 | 0.9 | 0.7 |
| 13. | Pronasale | 0.8 | 0.9 | 0.3 | 0.7 | 0.7 |
| 14. | Subnasale | 0.5 | 0.8 | 0.4 | 0.2 | 0.5 |
| 15. | Stomion | 0.6 | 1.0 | 0.9 | 0.5 | 0.8 |
| 16. | Promenton | 0.5 | 0.3 | 0.3 | 0.1 | 0.3 |
| 17. | Menton | 0.2 | 0.6 | 0.3 | 1.7 | 0.7 |
| 18. | L Cheilion | 0.2 | 2.3 | 1.0 | 0.6 | 1.0 |
| 19. | L Alare | 0.5 | 0.8 | 1.6 | 0.8 | 0.9 |
| 20. | L Gonion | 0.1 | 0.8 | 1.0 | 1.0 | 0.7 |
| 21. | L Tragion | 0.9 | 0.4 | 0.4 | 0.1 | 0.5 |

TABLE F-3. Continued

| No. | Landmark Name | Observer #1 | Observer #2 | Observer #3 | Observer #4 | Grand Mean |
|---|---|---|---|---|---|---|
| 22. | L Zygion | 0.5 | 0.4 | 0.6 | 0.4 | 0.5 |
| 23. | L Infraorbitale | 0.0 | 0.2 | 0.6 | 0.5 | 0.3 |
| 24. | L Ectoorbitale | 0.4 | 0.5 | 0.4 | 0.5 | 0.5 |
| 25. | L Zygofrontale | 0.7 | 1.5 | 0.5 | 0.1 | 0.7 |
| 26. | L Frontoemporale | 0.4 | 1.1 | 0.8 | 0.7 | 0.8 |
| 27. | Sellion | 0.4 | 0.2 | 0.3 | 0.4 | 0.3 |
| 28. | R Tragion | 0.1 | 1.2 | 0.1 | 1.3 | 0.7 |
| | GRAND MEAN ALL LANDMARKS | 0.42 | 0.79 | 0.55 | 0.64 | 0.61 |

TABLE F-4. Interobserver Error for the Wooden Headform Measured in the AHD (3-D distance values in millimeters; points not rotated).

| No. | Landmark Name | Observer #1 vs. Observer #2 | | | Observer #3 vs. Observer #4 | | | Mean-All Trials |
|---|---|---|---|---|---|---|---|---|
| | | Trial 1 | Trial 2 | Mean | Trial 1 | Trial 2 | Mean | |
| 1. | R Tragion | 0.2 | 0.6 | 0.4 | 0.8 | 0.2 | 0.5 | 0.5 |
| 2. | R Infraorbitale | 0.8 | 1.5 | 1.2 | 0.6 | 0.5 | 0.6 | 0.9 |
| 3. | R Alare | 1.6 | 1.1 | 1.4 | 0.7 | 0.1 | 0.4 | 0.9 |
| 4. | R Cheilion | 0.6 | 0.7 | 0.7 | 0.4 | 0.6 | 0.5 | 0.6 |
| 5. | R Gonion | 0.3 | 0.8 | 0.6 | 0.9 | 0.1 | 0.5 | 0.5 |
| 6. | R Zygion | 1.2 | 0.6 | 0.9 | 1.0 | 0.8 | 0.9 | 0.9 |
| 7. | R Ectoorbitale | 0.4 | 1.4 | 0.9 | 0.3 | 1.1 | 0.7 | 0.8 |
| 8. | R Zygofrontale | 0.7 | 0.3 | 0.5 | 0.4 | 0.4 | 0.4 | 0.5 |
| 9. | R Frontotemporale | 0.5 | 0.5 | 0.5 | 0.4 | 0.3 | 0.4 | 0.4 |
| 10. | Crinion | 0.4 | 0.5 | 0.5 | 0.2 | 0.6 | 0.4 | 0.4 |
| 11. | Glabella | 0.4 | 0.4 | 0.4 | 1.0 | 0.5 | 0.8 | 0.6 |
| 12. | Sellion | 0.6 | 1.1 | 0.9 | 0.5 | 0.9 | 0.7 | 0.8 |
| 13. | Pronasale | 0.5 | 0.6 | 0.6 | 1.0 | 0.2 | 0.6 | 0.6 |
| 14. | Subnasale* | 2.8 | 3.0 | 2.9 | 1.5 | 2.0 | 1.8 | 2.3 |
| 15. | Stomion | 1.1 | 1.5 | 1.3 | 0.6 | 1.7 | 1.2 | 1.2 |
| 16. | Promenton | 1.1 | 0.7 | 0.9 | 0.2 | 0.1 | 0.2 | 0.5 |
| 17. | Menton | 0.5 | 0.9 | 0.7 | 1.8 | 3.0 | 2.4 | 1.6 |
| 18. | L Cheilion | 1.8 | 0.8 | 1.3 | 0.5 | 0.2 | 0.4 | 0.8 |
| 19. | L Alare | 0.1 | 0.4 | 0.3 | 2.1 | 0.3 | 1.2 | 0.7 |
| 20. | L Gonion | 0.4 | 0.7 | 0.6 | 0.7 | 0.9 | 0.8 | 0.7 |
| 21. | L Tragion | 0.2 | 1.4 | 0.8 | 0.6 | 0.4 | 0.5 | 0.7 |

* Values reflect differences in measurement procedures used by operators in the Z axis.

TABLE F-4. Continued

| No. | Landmark Name | Observer #1 vs. Observer #2 | | | Observer #3 vs. Observer #4 | | | Mean-All Trials |
|---|---|---|---|---|---|---|---|---|
| | | Trial 1 | Trial 2 | Mean | Trial 1 | Trial 2 | Mean | |
| 22. | L Zygion | 0.8 | 0.6 | 0.7 | 0.9 | 0.6 | 0.8 | 0.7 |
| 23. | L Infraorbitale | 0.1 | 0.1 | 0.1 | 0.5 | 0.6 | 0.6 | 0.3 |
| 24. | L Ectoorbitale | 0.5 | 0.5 | 0.5 | 1.3 | 0.4 | 0.9 | 0.7 |
| 25. | L Zygofrontale | 0.8 | 0.4 | 0.6 | 0.1 | 0.7 | 0.4 | 0.5 |
| 26. | L Frontotemporale | 0.4 | 0.8 | 0.6 | 1.0 | 0.3 | 0.7 | 0.6 |
| 27. | Sellion | 0.4 | 0.4 | 0.4 | 1.1 | 0.4 | 0.8 | 0.6 |
| 28. | R Tragion | 0.5 | 0.2 | 0.4 | 0.4 | 0.9 | 0.7 | 0.5 |
| | GRAND MEAN (ALL LANDMARKS) | 0.72 | 0.80 | | 0.77 | 0.67 | | 0.74 |

TABLE F-5. Measured Values and Differences in X and Z Axes for the Wooden Headform Measured in the NATO and AHD Headboards (NATO and AHD values in millimeters = mean of two measurements).

| No. | Landmark Name | X AXIS | | | Z AXIS | | |
|---|---|---|---|---|---|---|---|
| | | NATO | AHD | DIFF. | NATO | AHD | DIFF. |
| 1. | R Tragion | 115 | 114 | 1.0 | 148 | 149 | 1.0 |
| 2. | R Infraorbitale | 203 | 201 | 2.0 | 145 | 144 | 1.0 |
| 3. | R Alare | 224 | 225 | 1.0 | 181 | 179 | 2.0 |
| 4. | R Cheilion | 208 | 209 | 1.0 | 223 | 221 | 2.0 |
| 5. | R Gonion | 139 | 140 | 1.0 | 211 | 211 | 0.0 |
| 6. | R Zygion | 161 | 160 | 1.0 | 159 | 160 | 1.0 |
| 7. | R Ectoorbitale* | - | 182 | - | - | 135 | - |
| 8. | R Zygofrontale | 197 | 197 | 0.0 | 116 | 115 | 1.0 |
| 9. | R Frontotemporale | 199 | 197 | 2.0 | 88 | 87 | 1.0 |
| 10. | Crinion | 218 | 214 | 4.0 | 74 | 72 | 2.0 |
| 11. | Glabella | 217 | 214 | 3.0 | 109 | 108 | 1.0 |
| 12. | Sellion | 216 | 213 | 3.0 | 127 | 126 | 1.0 |
| 13. | Pronasale | 251 | 249 | 2.0 | 178 | 177 | 1.0 |
| 14. | Subnasale | 228 | 228 | 0.0 | 191 | 189 | 2.0 |
| 15. | Stomion | 217 | 216 | 1.0 | 222 | 221 | 1.0 |
| 16. | Promenton | 207 | 207 | 0.0 | 255 | 255 | 0.0 |
| 17. | Menton | 194 | 195 | 1.0 | 270 | 269 | 1.0 |
| 18. | L Cheilion | 210 | 208 | 2.0 | 218 | 218 | 0.0 |
| 19. | L Alare | 222 | 221 | 1.0 | 178 | 176 | 2.0 |
| 20. | L Gonion | 131 | 128 | 3.0 | 206 | 206 | 0.0 |
| 21. | L Tragion | 107 | 102 | 5.0 | 145 | 146 | 1.0 |

* A different landmark (ectocanthus) was measured in the NATO headboard.

TABLE F-5. Continued

| No. Landmark Name | X AXIS | | | Z AXIS | | |
|---|---|---|---|---|---|---|
| | NATO | AHD | DIFF. | NATO | AHD | DIFF. |
| 22. L Zygion | 156 | 151 | 5.0 | 163 | 162 | 1.0 |
| 23. L Infraorbitale | 201 | 197 | 4.0 | 144 | 143 | 1.0 |
| 24. L Ectoorbitale* | - | 175 | - | - | 137 | - |
| 25. L Zygofrontale | 195 | 190 | 5.0 | 114 | 112 | 2.0 |
| 26. L Frontotemporale | 200 | 195 | 5.0 | 90 | 88 | 2.0 |
| 27. Sellion | 216 | 213 | 3.0 | 127 | 126 | 1.0 |
| 28. R Tragion | 115 | 114 | 1.0 | 148 | 149 | 1.0 |
| MEAN | | | 2.19 | | | 1.12 |

* A different landmark (ectocanthus) was measured in the NATO headboard.

TABLE F-6. Measured Values and Differences in Breadths for the Wooden Headform Measured by Calipers and AHD (values in millimeters = mean of four measurements).

| BREADTH | Landmarks -- Y Axis Distance | Caliper | AHD | Absolute Difference |
|---|---|---|---|---|
| Minimum Frontal | R Frontotemporale to L Frontotemporale | 113.0 | 112.0 | 1.0 |
| Maximum Frontal | R Zygofrontale to L Zygofrontale | 131.0 | 131.8 | 0.8 |
| Biinfraorbitale | R Infraorbitale to L Infraorbitale | 73.0 | 74.0 | 1.0 |
| Bitragion | R Tragion to L Tragion | 169.0 | 171.0 | 2.0 |
| Bizygomatic | R Zygion to L Zygion | 157.0 | 159.0 | 2.0 |
| Bigonial | R Gonion to L Gonion | 145.0 | 146.3 | 1.3 |
| Nose | R Alare to L Alare | 37.0 | 37.0 | 0.0 |
| Lip (Length) | R Cheilion to L Cheilion | 57.0 | 59.0 | 2.0 |

TABLE F-7. Mean Intraobserver Error for Ten Subjects Measured in the AHD (3-D distance values in millimeters; points are rotated).

| Landmark | Observer 1 Trial 1 vs. 2 | Observer 2 Trial 1 vs. 2 | Observer 3 Trial 1 vs. 2 | Observer 4 Trial 1 vs. 2 | Grand Mean |
|---|---|---|---|---|---|
| R Tragion | 1.9 | 1.6 | 1.5 | 1.3 | 1.58 |
| R Infraorbitale | 1.6 | 1.5 | 2.4 | 1.1 | 1.65 |
| R Alare | 1.1 | 1.3 | 1.7 | 1.5 | 1.40 |
| R Cheilion | 2.0 | 1.7 | 2.0 | 2.0 | 1.93 |
| R Gonion | 2.6 | 2.0 | 3.6 | 2.4 | 2.65 |
| R Zygion | 2.3 | 2.2 | 2.2 | 1.6 | 2.08 |
| R Ectoorbitale | 1.9 | 1.7 | 2.1 | 1.5 | 1.80 |
| R Zygofrontale | 1.7 | 1.7 | 1.9 | 1.2 | 1.63 |
| R Frontotemporale | 2.2 | 1.8 | 2.1 | 1.5 | 1.90 |
| Crinion | 2.6 | 2.1 | 3.2 | 2.5 | 2.60 |
| Glabella | 1.4 | 1.4 | 1.9 | 1.6 | 1.58 |
| Sellion | 0.8 | 0.8 | 0.8 | 0.8 | 0.80 |
| Pronasale | 1.3 | 1.4 | 6.2† | 1.0 | 1.23* |
| Subnasale | 1.5 | 1.9 | 3.9† | 1.4 | 1.60* |
| Stomion | 1.9 | 2.8 | 4.3† | 1.8 | 2.17* |
| Promenton | 2.5 | 2.0 | 5.2† | 2.3 | 2.27* |
| Menton | 2.9 | 2.6 | 3.9† | 2.5 | 2.67* |
| L Cheilion | 3.3 | 2.7 | 3.9† | 2.2 | 2.73* |
| L Alare | 2.2 | 1.9 | 2.0 | 1.7 | 1.95 |
| L Gonion | 2.7 | 2.6 | 3.1 | 2.5 | 2.73 |
| L Tragion | 1.5 | 1.2 | 1.0 | 1.3 | 1.25 |
| L Zygion | 1.7 | 1.7 | 2.1 | 2.3 | 1.95 |
| L Infraorbitale | 1.8 | 1.3 | 1.8 | 1.9 | 1.70 |
| L Ectoorbitale | 4.8† | 1.9 | 2.4 | 1.8 | 2.03* |
| L Zygofrontale | 1.6 | 1.7 | 2.2 | 1.8 | 1.83 |
| L Frontotemporale | 1.8 | 1.8 | -** | 2.1 | 1.90 |
| Sellion | 1.6 | 1.2 | -** | 2.0 | 1.60 |
| R Tragion | 2.4 | 2.1 | -** | 1.9 | 2.13 |
| Mean - All Landmarks | 1.96* | 1.81 | 2.11* | 1.77 | 1.91 |

† = probable error in a file due to mismeasurement or faulty sequencing.

* = erroneous values were not included when calculating the mean.

** = data lost for one trial during processing.

TABLE F-8. Mean Interobserver Error for Ten Subjects Measured in the AHD in Trial 2 by the Four Operators (3-D distance values in millimeters; points are rotated).

| Landmark | Observer 1 vs. Observer 2 | Observer 1 vs. Observer 3 | Observer 1 vs. Observer 4 | Observer 2 vs. Observer 3 | Observer 2 vs. Observer 4 | Observer 3 vs. Observer 4 | Grand Mean |
|---|---|---|---|---|---|---|---|
| R Tragion | 1.4 | 1.8 | 1.2 | 1.8 | 0.9 | 1.8 | 1.48 |
| R Infraorbitale | 1.7 | 2.3 | 1.5 | 2.3 | 1.5 | 1.9 | 1.87 |
| R Alare | 1.4 | 1.6 | 1.5 | 1.6 | 1.4 | 1.5 | 1.50 |
| R Cheilion | 2.2 | 2.9 | 2.7 | 2.6 | 3.0 | 3.2 | 2.77 |
| R Gonion | 2.5 | 3.1 | 2.4 | 3.4 | 2.1 | 3.3 | 2.80 |
| R Zygion | 2.2 | 2.5 | 1.6 | 2.5 | 1.6 | 2.1 | 2.08 |
| R Ectoorbitale | 2.0 | 2.5 | 1.8 | 2.5 | 1.9 | 2.4 | 2.18 |
| R Zygofrontale | 1.6 | 1.8 | 1.5 | 2.2 | 1.6 | 1.8 | 1.75 |
| R Frontotemporale | 1.5 | 1.7 | 1.1 | 2.1 | 1.6 | 1.6 | 1.60 |
| Crinion | 3.2 | 3.0 | 3.2 | 2.5 | 3.6 | 2.8 | 3.05 |
| Glabella | 1.5 | 1.7 | 1.5 | 1.6 | 1.5 | 1.7 | 1.58 |
| Sellion | 1.4 | 1.4 | 1.3 | 1.2 | 1.1 | 0.5 | 1.15 |
| Pronasale | 1.4 | 5.9† | 1.2 | 5.5† | 1.1 | 5.6† | 1.23* |
| Subnasale | 1.8 | 2.2 | 2.1 | 1.4 | 1.9 | 1.9 | 1.88 |
| Stomion | 2.7 | 2.9 | 2.0 | 3.2 | 2.4 | 2.7 | 2.65 |

† = probable error in a file due to mismeasurement or faulty sequencing.

* = erroneous values were not included when calculating the mean.

TABLE F-8. Continued.

| Landmark | Observer 1 vs. Observer 2 | Observer 1 vs. Observer 3 | Observer 1 vs. Observer 4 | Observer 2 vs. Observer 3 | Observer 2 vs. Observer 4 | Observer 3 vs. Observer 4 | Grand Mean |
|---|---|---|---|---|---|---|---|
| Promenton | 2.3 | 5.0† | 2.8 | 4.9† | 2.2 | 4.5† | 2.43* |
| Menton | 2.5 | 3.3 | 3.2 | 2.7 | 2.3 | 2.5 | 2.75 |
| L Cheilion | 3.1 | 3.2 | 3.2 | 3.1 | 3.2 | 2.5 | 3.05 |
| L Alare | 2.6 | 2.2 | 2.7 | 1.9 | 2.0 | 1.5 | 2.15 |
| L Gonion | 2.2 | 2.6 | 2.5 | 2.6 | 2.4 | 2.6 | 2.48 |
| L Tragion | 1.0 | 1.6 | 1.4 | 1.0 | 0.8 | 1.5 | 1.22 |
| L Zygion | 2.3 | 2.2 | 2.1 | 2.2 | 1.8 | 2.2 | 2.13 |
| L Infraorbitale | 1.9 | 2.0 | 2.0 | 1.3 | 1.7 | 1.6 | 1.75 |
| L Ectoorbitale | 4.9(†) | 5.2(†) | 5.4(†) | 2.0 | 1.6 | 2.2 | 1.93* |
| L Zygofrontale | 2.1 | 1.8 | 1.9 | 1.7 | 1.9 | 1.6 | 1.83 |
| L Frontotemporale | 1.9 | 2.9 | 2.1 | 2.9 | 1.9 | 2.6 | 2.38 |
| Sellion | 1.8 | 2.5 | 2.2 | 2.0 | 1.8 | 2.2 | 2.08 |
| R Tragion | 2.1 | 2.9 | 2.0 | 2.1 | 1.5 | 2.5 | 2.18 |
| Grand Mean - All Landmarks | 2.01* | 2.34* | 2.03* | 2.17* | 1.87* | 2.10* | 2.09 |

† = probable error in a file due to mismeasurement or faulty sequencing.

* = erroneous values were not included when calculating the mean.

TABLE F-9. Differences Between Mean Values of Non-rotated and Rotated Data Sets for Ten Subjects Measured by Observer 1 and Observer 2 in the AHD (3-D distance values in millimeters).

| | INTRAOBSERVER, TRIAL 1 vs. TRIAL 2 | | | | | | INTEROBSERVER OBSERVER 1 vs. OBSERVER 2 TRIAL 2 | | |
|---|---|---|---|---|---|---|---|---|---|
| | **OBSERVER 1** | | | **OBSERVER 2** | | | | | |
| Landmark | Non-Rotated | Rotated | Diff. | Non-Rotated | Rotated | Diff. | Non-Rotated | Rotated | Diff. |
| R Tragion | 3.6 | 1.9 | 1.7 | 2.5 | 1.6 | 0.9 | 3.8 | 1.4 | 2.4 |
| R Infraorbitale | 3.5 | 1.6 | 1.9 | 3.3 | 1.5 | 1.8 | 3.9 | 1.7 | 2.2 |
| R Alare | 4.4 | 1.1 | 3.3 | 3.9 | 1.3 | 2.6 | 4.8 | 1.4 | 3.4 |
| R Cheilion | 4.8 | 2.0 | 2.8 | 4.8 | 1.7 | 3.1 | 5.3 | 2.2 | 3.1 |
| R Gonion | 3.8 | 2.6 | 1.2 | 3.6 | 2.0 | 1.6 | 4.2 | 2.5 | 1.7 |
| R Zygion | 3.2 | 2.3 | 0.9 | 3.0 | 2.2 | 0.8 | 3.5 | 2.2 | 1.3 |
| R Ectoorbitale | 3.9 | 1.9 | 2.0 | 3.1 | 1.7 | 1.4 | 4.0 | 2.0 | 2.0 |
| R Zygofrontale | 3.5 | 1.7 | 1.8 | 2.8 | 1.7 | 1.1 | 4.1 | 1.6 | 2.5 |
| R Frontotemporale | 4.3 | 2.2 | 2.1 | 2.8 | 1.8 | 1.0 | 4.0 | 1.5 | 2.5 |
| Crinion | 4.2 | 2.6 | 1.6 | 2.9 | 2.1 | 0.8 | 3.9 | 3.2 | 0.7 |
| Glabella | 4.0 | 1.4 | 2.6 | 3.2 | 1.4 | 1.8 | 4.4 | 1.5 | 2.9 |
| Sellion | 3.9 | 0.8 | 3.1 | 3.5 | 0.8 | 2.7 | 4.8 | 1.4 | 3.4 |
| Pronasale | 4.3 | 1.3 | 3.0 | 4.1 | 1.4 | 2.7 | 5.5 | 1.4 | 4.1 |
| Subnasale | 4.5 | 1.5 | 3.0 | 4.0 | 1.[illegible] | 2.1 | 5.3 | 1.8 | 3.5 |
| Stomion | 4.3 | 1.9 | 2.4 | 4.0 | 2.8 | 1.2 | 4.9 | 2.7 | 2.2 |

TABLE F-9. Continued.

| Landmark Name | INTRA-OBSERVER, TRIAL 1 vs. TRIAL 2 — OBSERVER 1: Non-Rotated | Rotated | Diff. | OBSERVER 2: Non-Rotated | Rotated | Diff. | INTEROBSERVER OBSERVER 1 vs. OBSERVER 2 — TRIAL 2: Non-Rotated | Rotated | Diff. |
|---|---|---|---|---|---|---|---|---|---|
| Promenton | 4.8 | 2.5 | 2.3 | 4.4 | 2.0 | 2.4 | 5.2 | 2.3 | 2.9 |
| Menton | 5.1 | 2.9 | 2.2 | 5.2 | 2.6 | 2.6 | 5.5 | 2.5 | 3.0 |
| L Chelion | 5.0 | 3.3 | 1.7 | 3.5 | 2.7 | 0.8 | 4.6 | 3.1 | 1.5 |
| L Alare | 4.2 | 2.2 | 2.0 | 3.4 | 1.9 | 1.5 | 5.4 | 2.6 | 2.8 |
| L Gonion | 3.8 | 2.7 | 1.1 | 3.7 | 2.6 | 1.1 | 4.1 | 2.2 | 1.9 |
| L Tragion | 2.8 | 1.5 | 1.3 | 2.0 | 1.2 | 0.8 | 2.9 | 1.0 | 1.9 |
| L Zygion | 2.8 | 1.7 | 1.1 | 2.6 | 1.7 | 0.9 | 3.0 | 2.3 | 0.7 |
| L Infraorbitale | 3.4 | 1.8 | 1.6 | 3.4 | 1.3 | 2.1 | 4.2 | 1.9 | 2.3 |
| L Ectoorbitale | 5.9* | 4.8* | 1.1 | 3.4 | 1.9 | 1.5 | 6.2 | 4.9* | 1.3 |
| L Zygofrontale | 3.0 | 1.6 | 1.4 | 3.3 | 1.7 | 1.6 | 3.3 | 2.1 | 1.2 |
| L Frontotemporale | 3.4 | 1.8 | 1.6 | 3.5 | 1.8 | 1.7 | 3.0 | 1.9 | 1.1 |
| Sellion | 3.5 | 1.6 | 2.1 | 3.6 | 1.2 | 2.4 | 4.3 | 1.8 | 2.5 |
| R Tragion | 3.0 | 2.4 | 0.6 | 2.1 | 2.1 | 0.0 | 3.8 | 2.1 | 1.7 |
| Grand Mean - All Landmarks | 3.89 | 1.96 | 1.91 | 3.41 | 1.81 | 1.61 | 4.35 | 2.11 | 2.24 |

* = probable error in a file due to mismeasurement or faulty sequencing.

TABLE F-10. Intraobserver Differences in X and Y Axes for Six Subjects Measured in the NATO Headboard (values in millimeters).

| Landmark | X AXIS (from the wall) | | | | | Z AXIS (from the vertex) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | OBSERVER 1 T1* vs T2** | | OBSERVER 2 T1 vs T2 | | GRAND MEAN | OBSERVER 1 T1 vs T2 | | OBSERVER 2 T1 vs T2 | | GRAND MEAN |
| | Range | Mean | Range | Mean | | Range | Mean | Range | Mean | |
| R Tragion | 1-5 | 2.8 | 0-5 | 2.5 | 2.65 | 0-2 | 1.2 | 0-2 | 1.0 | 1.10 |
| R Infraorbitale | 0-6 | 2.7 | 0-7 | 2.0 | 2.35 | 0-6 | 2.2 | 0-11 | 4.2 | 3.20 |
| R Alare | 0-5 | 2.7 | 0-12 | 3.0 | 2.85 | 2-6 | 3.8 | 1-14 | 5.0 | 4.40 |
| R Cheilion | 3-5 | 3.8 | 1-17 | 4.7 | 4.25 | 1-7 | 3.3 | 1-14 | 4.7 | 4.00 |
| R Gonion | 0-6 | 3.0 | 0-14 | 4.2 | 3.60 | 0-3 | 1.8 | 0-7 | 2.2 | 2.00 |
| R Zygion | 1-4 | 2.3 | 1-7 | 2.8 | 2.55 | 0-4 | 1.5 | 0-7 | 2.2 | 1.85 |
| R Ectoorbitale | 1-6 | 2.8 | 0-6 | 2.2 | 2.50 | 0-5 | 2.7 | 1-13 | 4.7 | 3.70 |
| R Zygofrontale | 1-4 | 2.2 | 1-5 | 2.5 | 2.35 | 0-5 | 2.0 | 1-11 | 4.2 | 3.10 |
| R Frontotemporale | 1-4 | 2.5 | 0-3 | 1.8 | 2.15 | 0-5 | 2.2 | 1-12 | 4.2 | 3.20 |
| Crinion | 0-4 | 1.8 | 0-6 | 2.2 | 2.00 | 0-7 | 3.2 | 1-11 | 4.0 | 3.60 |
| Glabella | 0-4 | 1.7 | 0-3 | 1.3 | 1.50 | 1-7 | 4.0 | 1-15 | 4.8 | 4.40 |
| Sellion | 0-2 | 1.2 | 0-5 | 1.7 | 1.45 | 1-8 | 4.2 | 0-16 | 5.0 | 4.60 |
| Pronasale | 0-6 | 3.0 | 2-5 | 2.7 | 2.85 | 0-6 | 3.7 | 0-18 | 5.3 | 4.50 |
| Subnasale | 0-5 | 3.0 | 1-9 | 3.0 | 3.00 | 0-7 | 2.8 | 1-17 | 5.0 | 3.90 |
| Stomion | 0-7 | 3.5 | 0-14 | 4.3 | 3.90 | 0-7 | 3.7 | 1-16 | 4.7 | 4.20 |
| Promenton | 0-8 | 4.0 | 1-18 | 6.5 | 5.25 | 1-5 | 2.5 | 1-11 | 4.5 | 3.50 |
| Menton | 1-8 | 4.8 | 1-18 | 5.7 | 5.25 | 0-5 | 2.5 | 0-11 | 3.7 | 3.10 |
| Grand Mean - All Landmarks | 0.53-5.24 | 2.81 | 0.47-9.06 | 3.12 | | 0.35-5.59 | 2.78 | 0.59-12.12 | 4.08 | |

* T1 = Trial 1
** T2 = Trial 2

TABLE F-11. Interobserver Differences in X and Y Axes for Six Subjects Measured in the NATO Headboard (values in millimeters).

| Landmark | **X AXIS** (from the wall) OBSERVER 1 vs. OBSERVER 2 | | | | | **Z AXIS** (from the vertex) OBSERVER 1 vs. OBSERVER 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Trial 1 | | Trial 2 | | Grand | Trial 1 | | Trial 2 | | Grand |
| | Range | Mean | Range | Mean | Mean | Range | Mean | Range | Mean | Mean |
| R Tragion | 0-8 | 4.5 | 1-12 | 3.8 | 4.15 | 0-3 | 1.5 | 0-4 | 1.8 | 1.65 |
| R Infraorbitale | 0-5 | 2.7 | 1-11 | 4.0 | 3.35 | 1-13 | 5.7 | 0-11 | 6.3 | 6.00 |
| R Alare | 0-11 | 5.2 | 0-12 | 5.8 | 5.50 | 3-18 | 8.7 | 2-14 | 8.5 | 8.60 |
| R Cheilion | 3-14 | 7.3 | 1-18 | 7.8 | 7.55 | 2-14 | 6.2 | 1-14 | 7.2 | 6.70 |
| R Gonion | 0-11 | 5.3 | 1-15 | 5.5 | 5.40 | 0-5 | 2.3 | 1-5 | 2.7 | 2.50 |
| R Zygion | 1-7 | 4.0 | 0-11 | 3.[illegible] | 3.60 | 0-7 | 3.8 | 1-8 | 3.5 | 3.65 |
| R Ectoorbitale | 0-7 | 3.8 | 1-12 | 3.5 | 3.65 | 2-18 | 7.8 | 2-10 | 6.5 | 7.15 |
| R Zygofrontale | 1-6 | 2.8 | 0-9 | 2.8 | 2.80 | 2-14 | 6.0 | 0-10 | 5.8 | 5.90 |
| R Frontotemporale | 0-6 | 2.5 | 0-7 | 2.7 | 2.60 | 1-15 | 8.3 | 3-10 | 7.0 | 7.65 |
| Crinion | 2-8 | 4.7 | 1-6 | 3.7 | 4.20 | 1-17 | 7.7 | 1-9 | 6.2 | 6.95 |
| Glabella | 0-3 | 1.5 | 0-2 | 1.2 | 1.35 | 0-18 | 6.5 | 2-13 | 8.0 | 7.25 |
| Sellion | 0-6 | 2.2 | 1-7 | 3.0 | 2.60 | 1-17 | 7.8 | 0-14 | 7.3 | 7.55 |
| Pronasale | 0-10 | 4.0 | 1-6 | 4.3 | 4.15 | 2-19 | 7.8 | 0-18 | 9.5 | 8.65 |
| Subnasale | 1-13 | 5.0 | 2-10 | 6.3 | 5.65 | 2-17 | 7.7 | 1-15 | 8.5 | 8.10 |
| Stomion | 4-17 | 8.7 | 3-11 | 7.5 | 8.10 | 1-15 | 7.8 | 2-13 | 7.2 | 7.50 |
| Promenton | 3-21 | 9.2 | 5-13 | 7.7 | 8.45 | 0-15 | 6.8 | 2-20 | 8.8 | 7.80 |
| Menton | 2-22 | 8.7 | 4-12 | 8.0 | 8.35 | 0-12 | 4.8 | 0-8 | 5.0 | 4.90 |
| Grand Mean - All Landmarks | 1.00-10.12 | 4.83 | 1.29-10.24 | 4.75 | | 1.06-13.18 | 6.31 | 1.06-11.53 | 6.46 | |

TABLE F-12. Intraobserver Differences in the X and Z Axes for Six Subjects Measured in the AHD and the NATO Headboard (values in millimeters).

| Landmark | X Axis | | | | Z Axis | | | | Grand Average | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Observer 1 | | Observer 2 | | Observer 1 | | Observer 2 | | | |
| | Trial 1 | Trial 2 | Trial 1 | Trial 2 | Trial 1 | Trial 2 | Trial 1 | Trial 2 | X | Z |
| R Tragion | 1.6 | 4.9 | 4.9 | 5.0 | 1.7 | 2.2 | 1.2 | 1.0 | 4.10 | 1.53 |
| R Infraorbitale | 2.1 | 2.9 | 3.7 | 5.2 | 3.5 | 2.5 | 4.0 | 4.7 | 3.48 | 3.68 |
| R Alare | 2.5 | 2.2 | 5.3 | 6.2 | 3.9 | 2.9 | 5.4 | 6.0 | 4.05 | 4.55 |
| R Cheilion | 2.8 | 3.0 | 6.2 | 8.0 | 3.3 | 2.3 | 4.0 | 6.1 | 5.00 | 3.93 |
| R Gonion | 2.4 | 3.9 | 6.0 | 7.6 | 1.9 | 2.0 | 2.0 | 2.1 | 4.98 | 2.00 |
| R Zygion | 1.7 | 3.6 | 3.4 | 4.6 | 2.6 | 2.6 | 2.5 | 2.4 | 3.33 | 2.53 |
| R Ectoorbitale | 2.3 | 3.1 | 3.8 | 5.1 | 4.7 | 2.7 | 5.3 | 4.7 | 3.58 | 4.35 |
| R Zygofrontale | 1.5 | 3.1 | 2.4 | 3.0 | 3.9 | 3.7 | 4.6 | 3.7 | 2.50 | 3.98 |
| R Frontotemporale | 1.4 | 3.2 | 2.5 | 2.2 | 5.1 | 2.5 | 4.2 | 5.0 | 2.33 | 4.20 |
| Crinion | 5.9 | 5.2 | 3.8 | 2.0 | 5.7 | 5.0 | 5.1 | 6.8 | 4.23 | 5.65 |
| Glabella | 3.4 | 3.0 | 4.0 | 3.8 | 4.5 | 2.5 | 6.1 | 6.0 | 3.55 | 4.78 |
| Sellion | 2.5 | 2.6 | 4.2 | 5.2 | 4.1 | 3.0 | 5.3 | 5.8 | 3.63 | 4.55 |
| Pronasale | 2.5 | 1.9 | 5.5 | 5.3 | 4.5 | 3.3 | 6.8 | 7.4 | 3.80 | 5.50 |
| Subnasale | 2.9 | 1.7 | 4.3 | 5.6 | 5.1 | 4.9 | 5.7 | 6.2 | 3.63 | 5.48 |
| Stomion | 3.2 | 2.8 | 7.1 | 7.6 | 3.4 | 3.6 | 6.0 | 6.4 | 5.18 | 4.85 |
| Promenton | 3.9 | 1.6 | 6.7 | 7.8 | 3.0 | 2.4 | 4.8 | 6.6 | 5.00 | 4.20 |
| Menton | 5.4 | 2.6 | 7.1 | 8.0 | 3.0 | 2.3 | 4.5 | 5.5 | 5.78 | 3.83 |
| Grand Mean - All Landmarks | 2.82 | 3.02 | 4.76 | 5.42 | 3.76 | 2.96 | 4.56 | 5.08 | | |

TABLE F-13. Mean Absolute Differences Between Caliper and AHD Measured Breadths for Six Subjects (values in millimeters).

| Landmark | Observer 1 Trial 1 | Observer 1 Trial 2 | Observer 2 Trial 1 | Observer 2 Trial 2 | Grand Mean |
|---|---|---|---|---|---|
| Minimum Frontal | 2.5 | 3.0 | 1.6 | 1.6 | 2.18 |
| Maximum Frontal | 3.9 | 3.4 | 2.1 | 2.0 | 2.85 |
| Biectoorbitale | 4.3 | 4.7 | 2.3 | 1.6 | 3.23 |
| Biinfraorbitale | 1.6 | 1.3 | 1.1 | 0.8 | 1.20 |
| Bitragion | 3.1 | 2.3 | 4.5 | 5.0 | 3.73 |
| Bizygomatic | 5.5 | 5.5 | 3.6 | 4.2 | 4.70 |
| Bigonial | 10.0 | 10.7 | 14.4 | 12.4 | 11.88 |
| Nose | 1.0 | 0.9 | 0.6 | 0.5 | 0.75 |
| Lip (Length) | 1.4 | 1.5 | 1.5 | 1.2 | 1.40 |
| Grand Mean All Breadths | 3.70 | 3.70 | 3.52 | 3.26 | |